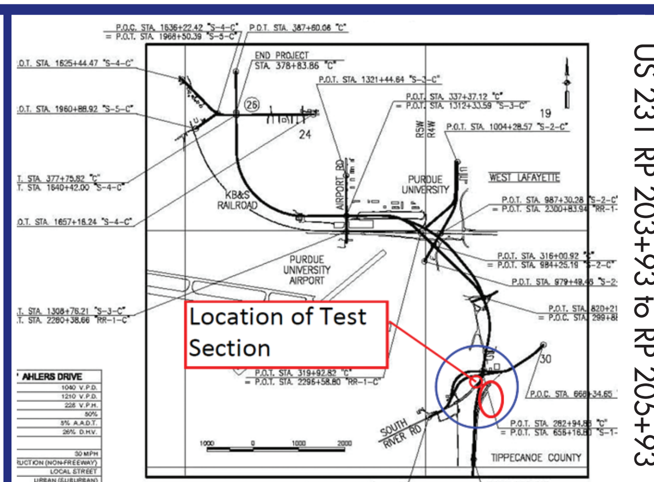
JOINT TRANSPORTATION RESEARCH PROGRAM
INDIANA DEPARTMENT OF TRANSPORTATION AND PURDUE UNIVERSITY

Using Recycled Concrete as Aggregate in Concrete Pavements to Reduce Materials Cost



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SPR-3309 • Report Number: FHWA/IN/JTRP-2013/18 • DOI: 10.5703/1288284315220

RECOMMENDED CITATION

Verian, K. P., N. M. Whiting, J. Olek, J. Jain, and M. B. Snyder. *Using Recycled Concrete as Aggregate in Concrete Pavements to Reduce Materials Cost*. Publication FHWA/IN/JTRP-2013/18. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, 2013. doi: 10.5703/1288284315220.

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JOINT TRANSPORTATION RESEARCH PROGRAM

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NOTICE

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/IN/JTRP-2013/18		

4. Title and Subtitle	5. Report Date
Using Recycled Concrete as Aggregate in Concrete Pavements to Reduce Materials Cost	August 2013
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Kho Pin Verian, Nancy M. Whiting, Jan Olek, Jitendra Jain, Mark B. Snyder	FHWA/IN/JTRP-2013/18
9. Performing Organization Name and Address Joint Transportation Research Program Purdue University 550 Stadium Mall Drive West Lafayette, IN 47907-2051	10. Work Unit No.
	11. Contract or Grant No. SPR-3309
12. Sponsoring Agency Name and Address Indiana Department of Transportation State Office Building 100 North Senate Avenue Indianapolis, IN 46204	13. Type of Report and Period Covered Final Report
	14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the Indiana Department of Transportation and Federal Highway Administration.

16. Abstract

The main objective of this project was to evaluate the effects of using aggregate produced from crushed concrete pavement as a replacement for natural (virgin) coarse aggregate in pavement mixtures. A total of ten different concrete mixtures containing recycled concrete aggregate (RCA) were designed to meet the requirements of Indiana Department of Transportation (INDOT) specifications. These included three different RCA replacement levels (30%, 50% and 100% by weight of the natural coarse aggregate) and two different cementitious systems (plain system – Type I portland cement only and fly ash system – 80% of Type I portland cement and 20% of ASTM C 618 Class C fly ash). The scope of the project included the evaluation and comparison of several properties of RCA and natural aggregates, evaluation and analysis of the effects of RCA on concrete properties, and modification of aggregate gradations and mixture composition in an attempt to improve the properties of RCA concrete.

All ten mixtures were first produced in the laboratory (trial batches) and were subsequently reproduced in the commercial ready-mixed concrete plant. Each mixture produced in the ready-mixed plant was used to prepare several types of specimens for laboratory testing. The tests performed on fresh concrete included determination of slump and entrained air content. The mechanical properties of the hardened concrete were assessed by conducting compressive strength, flexural strength, modulus of elasticity and Poisson's ratio tests.

Concrete durability was assessed using a wide array of measurements, including: rapid chloride permeability (RCP), rapid chloride migration (RCM), electrical impedance spectroscopy (EIS), surface resistivity, free shrinkage, water absorption test, freeze-thaw resistance and scaling resistance.

The test results indicated that the properties of plain (no fly ash) concrete mixtures with 30% RCA as coarse aggregate were very comparable to (in some cases even better than) those of the control concrete (0% RCA). Although mixtures with 50% RCA showed a reduction in durability and mechanical properties of up to 36%, the test results still met INDOT's specifications requirements. The mechanical properties of plain concretes made with 100% RCA were measurably lower (16%-25%) than those of the control concrete. It should be pointed out, however, that these properties were still above the minimums required by INDOT's specifications except for one mixture in which the w/c was increased to 0.47 to achieve workability. The use of fly ash improved the strength and durability of RCA concrete, especially at later ages. In particular, the properties of concrete with 50% RCA coarse aggregate were similar to the properties of control concrete. Similarly, the mechanical and durability properties of the mixture with 100% RCA coarse aggregate and 20% fly ash were better than those of a similar mixture prepared without fly ash. Even though, when compared to the fly ash concrete with 100% virgin aggregate the mechanical and durability properties of the 100% RCA concrete were up to 19% and 35% lower, it still met minimum requirements imposed by INDOT's specifications.

17. Key Words	18. Distribution Statement
recycled concrete aggregate (RCA), pavement concrete, compressive strength, flexural strength, durability, rapid chloride permeability, electrical impedance spectroscopy, shrinkage, fly ash	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	68	

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EXECUTIVE SUMMARY

USING RECYCLED CONCRETE AS AGGREGATE IN CONCRETE PAVEMENTS TO REDUCE MATERIALS COST

Introduction

The main objective of this project was to evaluate the effects of using aggregate produced from crushed concrete pavement as a replacement for natural (virgin) coarse aggregate in new pavement mixtures. A total of ten different concrete mixtures containing recycled concrete aggregate (RCA) were designed to meet the requirements of the Indiana Department of Transportation (INDOT) specifications. These mixtures included three different RCA replacement levels of 30%, 50%, and 100% (by weight of the natural coarse aggregate) and two different cementitious systems (plain system—Type I Portland cement only and fly ash system—80% of Type I Portland cement and 20% of ASTM C 618 Class C fly ash). The scope of the project included the evaluation and comparison of several properties of RCA and natural aggregates, and evaluation and analysis of the effects of RCA on concrete properties.

All mixtures were first produced in the laboratory (trial batches), then subsequently reproduced in a commercial ready-mixed concrete plant. Each mixture produced in the ready-mixed plant was used to prepare several types of specimens for laboratory testing. The tests performed on fresh concrete included determination of slump and air content. The mechanical properties of the hardened concrete were assessed by conducting compressive strength, flexural strength, modulus of elasticity, and Poisson's ratio tests.

Concrete durability was assessed using a wide array of measurements, including: rapid chloride permeability (RCP), rapid chloride migration (RCM), electrical impedance spectroscopy (EIS), surface resistivity, free shrinkage, water absorption, freeze-thaw resistance, and scaling resistance tests.

After the ten concrete mixtures were tested, the original gradation was modified and six additional concrete mixtures were developed and produced in the laboratory. The original aggregate gradation was modified by adjusting the fine-to-coarse aggregate ratio and adding a mid-size #11 aggregate (Dmax = ½ in.). A mid-sized RCA coarse aggregate was introduced that was crushed from mixed-use concrete debris. These mixtures were used to study whether different sizes and proportions of virgin and RCA aggregates could be used to produce an "optimized blend" that improved one or more concrete characteristics, and to examine the influence of using a non-pavement concrete as RCA in new concrete mixtures.

Findings

Test results indicated that the properties of plain (no fly ash) concrete mixtures with 30% RCA as coarse aggregate were very comparable to, and in some cases even better than those of the control concrete (0% RCA). Plain concrete mixtures with 50% RCA and 100% RCA showed a reduction in durability and mechanical properties; however, they still passed all of INDOT's specifications requirements. The one exception was for the 100%RCA and no fly ash mixture in which the w/cm was increased to 0.47 to achieve workability (exceeding <0.45 w/cm target).

The use of fly ash improved the strength and durability of RCA concrete, especially at later ages. In particular, the properties of concrete with 50% RCA coarse aggregate were similar to the properties of the control concrete. Similarly, the mechanical and durability properties of the mixture with 100% RCA coarse aggregate and 20% fly ash were better than those of a similar mixture prepared without fly ash. Even though, when compared to the fly ash concrete with 100% virgin aggregate, the mechanical and durability properties of the 100% RCA concrete were lower, it still met minimum requirements imposed by INDOT's specifications.

The test results obtained from the six additional modified mixtures indicated that modifying the aggregate gradation with a mid-size RCA made from mixed-use concrete did not benefit either compressive or flexural strength values. The failure to improve concrete strength with these modified aggregate gradations may have been due, at least in part, to the quality of the mid-sized RCA aggregate used to modify the gradation.

The interactive benefit-cost analysis (BCA) developed under this project showed that using RCA can reduce aggregate costs, resulting in measureable project-wide savings. Cost savings, or lack of savings, related to using RCA can be readily identified using either project-specific inputs or general estimates.

In conclusion, this project demonstrated that quality, durable concrete that contains some level of RCA coarse aggregate made from old concrete pavements can be used in new concrete pavement structures. This practice can lead to good resource management, quality concrete pavements, and potential cost savings.

Implementation

Considering the limited scope of this study (only one source of RCA, one Class C fly ash, and two natural aggregate sources), and potential variability in RCA characteristics, it is recommended that the amount of RCA coarse aggregate be limited to 30% in plain concrete and 50% in fly ash concrete to ensure adequate quality of the pavement concrete.

The field trials demonstrated that RCA as 30% and 50% of the coarse aggregate in a concrete mixture without fly ash can be successfully produced and placed in slip-form paving using standard INDOT practices by traditional paving equipment. Future use should explore higher percentages of RCA replacement in shoulders and non-highway construction until confidence and experience is developed using RCA.

The benefit-cost analysis developed under this project is a useful tool to examine the costs of using RCA compared to natural aggregate in pavement structures. The BCA can identify cost savings and provide information valuable to users in resource management decisions.

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LIST OF ABBREVIATIONS

AASHTO:	American Association of State Highway and Transportation Officials
ASR:	Alkali Silica Reaction
ASTM:	American Society for Testing Material
BCA:	Benefit-Cost Analysis
CA:	Coarse Aggregate
CF:	Coarseness Factor
CTE:	Coefficient of Thermal Expansion
D_{nssm}:	Non-steady-state Migration Coefficient
DOT:	Department of Transportation
EIS:	Electrical Impedance of Spectroscopy
EMV:	Equivalent Mortar Volume
F/T:	Freezing and Thawing
INDOT:	Indiana Department of Transportation
ITZ:	Interfacial Transition Zone
NA:	Natural Aggregate
NC:	Normal Concrete (concrete with 100% natural aggregate)
NT:	Nord Test
PCC:	Portland Cement Concrete
PCCP:	Portland Cement Concrete Pavement
QC/QA:	Quality Control/Quality Assurance
RA:	Recycled Aggregate
RAC:	Recycled Aggregate Concrete
RCA:	Recycled Concrete Aggregate
RCM:	Rapid Chloride Migration
RCP:	Rapid Chloride Permeability
RFA:	Recycled Fine Aggregate
W/D:	Wetting and Drying
WF:	Workability Factor

1. INTRODUCTION

1.1 Background

Recycling, sustainability and environmental stewardship are all concepts that are becoming more common in many facets of life, including concrete paving. The greatest potential for reusing old concrete at a high value is to use it as aggregate in new concrete. Many times, this old concrete sits in unsightly piles, is land filled or is used as random fill or sub-base material.

On the other hand, natural aggregates, which consist of crushed stone or gravel and sand, constitute the major component of pavement concrete, occupying from 70% to 80% of the volume of concrete mixtures (*1*). Natural aggregate resources are vast but finite, and aggregate resources are being depleted, especially near urban areas (*2*). Environmental regulations and land use policies further limit the opening of new quarries or the expansion of existing aggregate quarries. Natural aggregate costs are expected to rise with scarcity of sources and increasing haul distances (*2*). Using recycled concrete aggregate (RCA) as a substitute for natural (virgin) aggregates is a way to potentially address these economic and environmental concerns.

1.2 Literature Review

Concrete pavements are 100 percent recyclable (*2*). Over the past 30 years, many DOTs have recycled concrete as aggregate back into concrete pavements with somewhat mixed results. There have been some failures, but many other pavements are still performing well after several decades of service (*2*). The use of RCA in concrete may alter the properties of the concrete and may affect its performance. RCA often has lower specific gravity and higher absorption values compared to those of natural aggregate (*2,3*) which, in turn, may affect the workability of fresh concrete (*3–6*). Various researchers measured specific gravities that ranged from 2.1 to 2.6, and absorption values that ranged from 3.3% to 9.25% for different RCA.

In hardened concrete made with RCA, many researchers generally found decreased values of compressive strength (up to 30%), tensile strength (up to 40%), density (up to 5%) and modulus of elasticity (up to 40%) (*7–10*). These properties tended to decrease with increased levels of replacement of virgin aggregates with RCA when all other mix design parameters remained constant (*7–11*). An exception to this trend was found by Etxeberria et al. 2007 (*10*) where concrete with 30% RCA exhibited higher tensile strength than concrete without RCA.

Several solutions were proposed by other researchers that might help ensure the consistent quality of concrete made with RCA including:

- Controlling the percentage of RCA (*7,8,10*)
- Using pozzolanic materials (*12*)
- Modifying the mixing methodology (*13*)
- Proportioning mixtures using equivalent mortar volume (EMV) method (*14*)
- Controlling the initial moisture state of the aggregates (*9*)

A more thorough literature review is available in Appendix A of this document and in reference (*15*).

1.3 Research Objectives

The main objective of this study was to evaluate the effects of using recycled concrete aggregate (RCA) as a replacement for natural coarse aggregate on the fresh and hardened properties of concrete pavement mixtures.

1.4 Scope of Work

The scope of study included evaluation and comparison of several properties of RCA and natural aggregates, evaluation and analysis of the effects of RCA on fresh and hardened concrete properties, and modification of aggregate gradations and mixture composition in an attempt to improve the properties of RCA concrete. All mixtures were designed to meet the requirements of the Indiana Department of Transportation (INDOT) specifications Section 501 (QC/QA procedures) (*16*) as listed below:

- Minimum amount of Portland cement: 400 lb/yd^3
- Target water-to-cementitious ratio (w/cm): 0.42 ($\pm$0.03)
- Minimum Portland cement/fly ash ratio: 3.2 by weight (mass)
- Target air content of 6.5% (allowable range 5.7%–8.9%)
- Minimum flexural strength at 7 days: 570 psi (4 MPa)

A target slump of between 1.25–3.00 inches was adopted from the INDOT's Section 502 specifications for slip-form paving (non-QC/QA procedures).

1.5 Test Program

The materials used in this study are described in Table 1.1. Mill certificates for the cement and fly ash used are given in Appendix B.

Two different #8-size natural coarse aggregates (N1 and N2) were used in order to provide information on the effects of different natural coarse aggregate characteristics on the ranges of concrete properties made with and without RCA. The #8 RCA (8R) was crushed from a recently removed INDOT concrete pavement (SR 26 at Lafayette) that showed good durability performance during its service life of more than 35 years. The #11 RCA (11R) was produced from construction debris of various unknown sources.

This part of the study involved design and evaluation of two distinctive sets of mixtures: laboratory mixtures (L) and 10 plant-produced mixtures (P). The designs of nine laboratory mixtures were based on INDOT-approved mixture compositions supplied by concrete paving contractors (as shown in Table B.1, Appendix B) and refined through a trial batching process in the

TABLE 1.1
Materials used in the project

Material	Description	Specific gravity (SSD)	Absorption (%)
Cement	Type I Portland cement conforming to ASTM C 150	3.15	NA
Fly ash	Class C fly ash met the requirement of ASTM C 618 and AASHTO M 295	2.62	NA
Coarse aggregate N1	#8 Dolomitic Limestone 1, obtained from Delphi Plant, IN., produced by U.S. Aggregates, Inc., INDOT source #2421	2.74	1.8
Coarse aggregate N2	#8 Dolomitic Limestone 2, obtained from Newton County quarry, Kentland, IN., produced by Rogers Group, INDOT source #2445	2.69	2.7
Coarse aggregate R	#8 RCA, mostly gravel, crushed from State Road 26 Indiana by Milestone Contractor LP, IN	2.42	5.3
Coarse aggregate 11N1*	#11 Dolomitic Limestone 1 sieved from #8N1	2.74	1.8
Coarse aggregate 11R*	#11 RCA crushed from various types of concrete stockpiled by Reith-Riley Company, IN	2.45	5.4
Fine aggregate	#23 natural sand produced by Vulcan Materials located at Indiana (source #2183-Swisher Sand and Gravel)	2.61	1.4

NA = not applicable.
*Used in modified mixtures only.

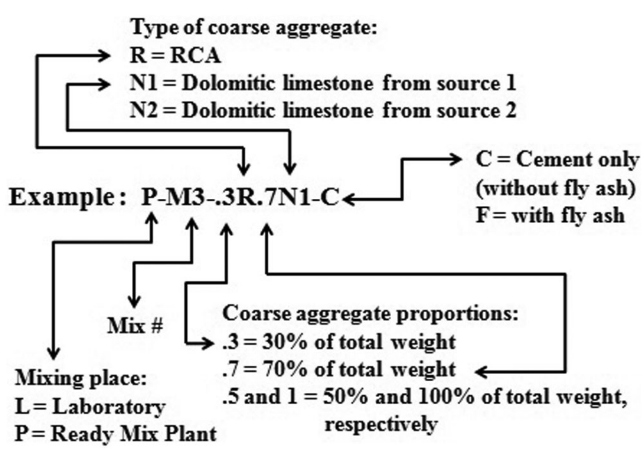


Figure 1.1 Mixture designation scheme for laboratory and ready-mixed batches.

lab (L). These mixture compositions are shown in Table B.2 of Appendix B. Each of the lab-produced trial batch mixtures (L) was tested for slump, density and air content. Flexural beams were tested after 7 days of moist curing. The summary of the test results is presented in Table B.2, Appendix B.

The 9 mixture designs then were reproduced in a ready-mixed plant with adjustments in w/cm and admixtures to achieve the target range of slump (1.25–3.00 inches) and air content (target 6.5%, allowable range 5.7%–8.9%) specified by INDOT. To differentiate the mixtures, a specific labeling scheme was developed for identifying each mixture, as shown in Figure 1.1.

In the end, 10 concrete mixtures were produced in the ready-mixed plant, as presented in Table 1.2. Mix-10 (P-M10-1N1-C) was an approximate replicate of Mix-1 (P-M1-1N1-C), because P-M1 was re-mixed three times during its production, which might have affected the concrete properties.

TABLE 1.2
Mixture proportions for concrete made in the ready-mixed plant (lbs/yd^3)

Mixture designation	P-M1-1N1-C	P-M2-1R-C	P-M3-.3R.7N1-C	P-M4-.5R.5N2-F	P-M5-.3R.7N1-F	P-M6-.5R.5N2-C	P-M7-1R-F	P-M8-.3R.7N2-F	P-M9-1N2-F	P-M10-1N1-C
Cement	522.5	510	512.5	432.5	432.5	515	445	437.5	437.5	512.5
Fly ash	—	—	—	100	100	—	105	100	110	—
Water	232	239	219	212	220	224	220	227	214	214
Fine aggregate	1570	1480	1520	1510	1480	1480	1420	1450	1480	1580
Coarse aggregate #8 N1	1690	—	1190	—	1130	—	—	—	—	1730
Coarse aggregate #8 N2	—	—	—	800	—	830	—	1130	1700	—
Coarse aggregate #8 RCA	—	1610	510	820	480	830	1580	490	—	—
Air entraining agent*	1.1	1.6	1.2	1.2	1.2	1.1	1.5	1.2	1.3	1.3
Water reducer*	1.9	2.0	2.0	2.1	1.9	1.7	2.4	2.1	1.8	2
w/cm	0.44	0.47	0.43	0.40	0.41	0.43	0.40	0.42	0.39	0.42

*fl oz/100 lbs cementitious.

TABLE 1.3
Tests performed for this project

	Aggregate test	Standard
	Sieve analysis and fineness modulus	AASHTO T 27
	Specific gravity and absorption*	AASHTO T 84
	Soundness (brine freeze and thaw)*	ITM 209
	L.A. abrasion	AASHTO T 96
	Organic impurities test in fine aggregate	AASHTO T 21
	Percent of mortar in RCA	ASTM C 295 (Modified)
	Uncompacted void content of coarse aggregate	AASHTO T 326
Atomic Absorption/Emission Spectrophotometer (Varian® SpectrAA–20) for determining the concentration of Potassium ion in leachate from coarse aggregates.		
Dionex Ion Chromatograph with Ionpac® AS4A Analytical column for determining Chloride and Sulfate ions in leachate from coarse aggregates.		
Concrete test		Standard
Fresh concrete (plastic phase)	Slump*	AASHTO T 119
	Air content, pressure method*	AASHTO T 152
	Air content, volumetric method*	ASTM C 173
Hardened concrete	Compressive strength	AASHTO T 22
	Flexural strength*	AASHTO T 97
	Shrinkage	ASTM C 157
	Modulus elasticity and Poisson's ratio	ASTM C 469
	Freezing and thawing (F/T)*	AASHTO T 161
	Electrical impedance spectroscopy (EIS)	—
	Surface resistivity	AASHTO TP 95
	Scaling	ASTM C 672
	Rapid chloride permeability (RCP) test	AASHTO 277
	Rapid chloride migration (RCM) test	NT Build 492
	Water absorption	ASTM C 1585
	Air dry density	—

*Test required by INDOT.
— = No specific standard being used. (The detail procedures can be found in reference (*15*).)

A comprehensive suite of tests was used to assess both the plastic and hardened properties of various concretes (see Table 1.3). The implementation of this suite of tests required fabricating 56 specimens and a small outdoor test slab ($2.5' \times 4' \times 1'$) from each of the plant mixtures. The test slabs were placed in order to test ease of placement, ability to finish, and long-term outdoor exposure. The outdoor slabs are located at the IMI mixing plant off US 25, north of West Lafayette, IN. Table 1.4 provides a detailed listing of the number

TABLE 1.4
Inventory of test specimens and tests performed

Test	Type of specimens (size, in)	Number of specimens/mix	Total specimens/mix
Compressive strength	Cylinder (4 × 8)	35	58
Modulus of elasticity and Poisson's ratio	Cylinder (4 × 8)	35	58
Density	Cylinder (4 × 8)	35	58
Rapid chloride permeability (RCP) test	Cylinder (4 × 8)	35	58
Rapid chloride migration (RCM) test	Cylinder (4 × 8)	35	58
Electrical impedance spectroscopy	Cylinder (4 × 8)	35	58
Surface resistivity	Cylinder (4 × 8)	35	58
Coefficient of thermal expansion (CTE)	Cylinder (4 × 8)	35	58
Water absorption	Cylinder (4 × 8)	35	58
Flexural strength	Prism (6 × 6 × 21)	12	58
Freeze/thaw	Prism (3 × 4 × 15)	5	58
Length change	Prism (3 × 3 × 11.5)	3	58
Scaling	Slab (7.5 × 10 × 3)	2	58
	Field slab*	1	58

*Size: $2.5' \times 4' \times 1'$.

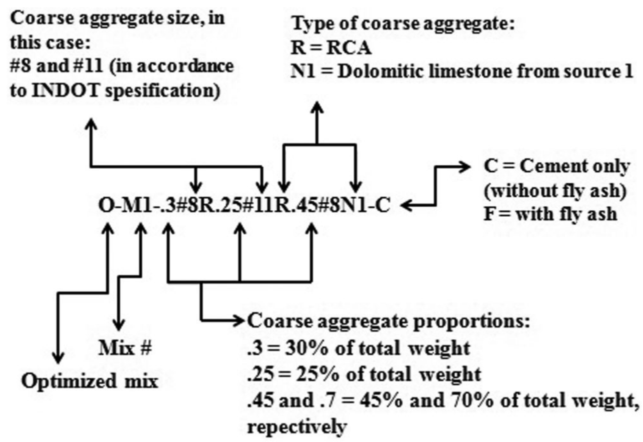


Figure 1.2 Designation scheme for mixtures with modified RCA gradations.

of specimens used for each type of test for each mixture design and the total number of specimens produced at the ready-mixed plant.

Besides the original nine lab mixtures, six additional mixtures were developed and batched in the laboratory using a modified gradation of aggregates (with respect to the original mixtures). These mixtures were used to study if the natural and RCA aggregates can be used in different proportions to produce an "optimized blend" which can improve some of the concrete characteristics. During this part of the project, mid-size #11 (D_{max} = ½ in.) aggregates were used to fill a gap in the combined gradation. The specific labeling scheme and the proportions of those additional lab mixtures are presented in Figure 1.2 and Table 1.5.

2. TEST RESULTS AND ANALYSIS

This chapter presents the experimental findings related to the nine laboratory mixtures and 10 plant-batched mixtures. These findings are presented in two sections, aggregate test results (Section 2.1) and concrete test results (Section 2.2). Results for the lab mixtures with modified gradations are presented in Chapter 3.

2.1 Aggregate Test Results

In all aggregate tests, aggregate sources were tested individually and not as a combined blend of materials unless otherwise stated. In addition to the aggregate tests identified in Table 1.3, the following tests on aggregate also were performed.

- The percent paste remaining on the RCA was estimated using a common petrographic method of point counting (*17*).
- The leachate potential were measured for each coarse aggregate by crushing it into a powder that passed the #100 sieve, diluting a 20-gram sample of the powder with 80 grams of deionized water, and analyzing the ions contained in that solution using atomic absorption and dionex ion chromatography.

The results are discussed below and more details are provided in Appendix C.

2.1.1 Sieve Analysis and Fineness Modulus

Sieve analysis test results showed that the fine aggregate used in this project met INDOT standard specification for #23 aggregate and all coarse aggregates used met the specification for #8's (see Figure C.1 in Appendix C).

TABLE 1.5
Mixture proportions for concrete with modified gradation (lbs/yd^3)

Materials	O-M1-.3#8R.25# 11R.45#8N1-C	O-M2-.3#11R.7 #8N1-C	O-M3-.3# 11R.7#8R-F	O-M4-.3# 11R.7#8R-C	O-M5-.3#8R.25# 11R.45#8N1-F	O-M6-.3#11N1.7 #8N1-C
Cement	515	515	400	515	440	515
Fly ash	—	—	100	—	100	—
Water	211.2	215.0	210.0	232.0	225.0	230.0
Fine aggregate	1330	1350	1300	1300	1320	1350
Coarse aggregate #8N1	790	1260	—	—	775	1300
Coarse aggregate #11N1	—	—	—	—	—	550
Coarse aggregate #8R	530	—	1200	1200	515	—
Coarse aggregate #11R	450	535	510	510	435	—
Air entraining agent*	0.8	0.5	0.9	0.9	0.8	0.8
Water reducer*	2.0	1.5	1.5	1.1	2.0	2.0
w/cm	0.41	0.42	0.42	0.45	0.42	0.45

*fl oz/100 lbs cementitious.

The combined aggregate gradations for all mixtures fell between INDOT's specified upper and lower limits. When these gradations were compared to an 8-18 gradation (*18*), all of them had excessive amounts of aggregate retained on the ½ in. sieve and insufficient aggregates retained on the #8 sieve (see Figure C.2; more details regarding the use of the 8-18 band can be found in reference (*18*)).

Based on the coarseness factor (CF) and workability factor (WF) identified using the Shilstone coarseness factor chart (*18*), all combined gradations used in the mixtures were classified as sandy, with CF ranging from 71.5 to 74.8 and WF from 44.7 to 47.9 (see Figure C.3, Appendix C).

2.1.2 Specific Gravity, Absorption and L.A. Abrasion

The aggregate test results for specific gravity, absorption and percent mass loss obtained from the L.A. abrasion test are shown in Table 2.1. The bulk specific gravity (SSD) of #8 coarse RCA (2.42) was lower than that of the #8 N1 (2.74) and #8 N2 (2.69). The #8 RCA had higher absorption (5.3%) than the #8 natural aggregates N1and N2 (1.8% and 2.7% respectively). The absorption of #8 RCA exceeded the maximum absorption value for AP aggregate specified by INDOT (5.0%).

The L.A. abrasion test determines the toughness/hardness of the aggregates and indicates how readily the aggregate may break down during batching, construction, transportation and handling. Although the natural aggregates had approximately 4% to 7% lower mass losses than the RCA, all the aggregates used in this research satisfied INDOT's requirement of 40% maximum mass loss for AP aggregate (*16*). See Table C.1, Appendix C for additional details.

2.1.3 Soundness (Brine Freeze and Thaw)

The aggregates' susceptibility to degradation upon exposure to repeated freezing and thawing cycles and other environmental conditions was estimated using ITM test 209 *Soundness of Aggregates by Freezing and Thawing in a Brine Solution*. These tests were performed at INDOT's Office of Materials Management lab.

The #8 RCA had a higher mass loss (16.4%) than that of either of the #8 natural aggregates (#8 N1 = 0.5%; #8 N2 = 0.9%). The fine aggregate used in this project had a mass loss of 7.8%. Based on these test, all fine and #8 coarse aggregates used in this project satisfied INDOT's ITM 209 maximum allowable mass loss requirements of 30% for AP coarse aggregate and 12% for PCC fine aggregates. See Table C.2 and Appendix C for additional details.

2.1.4 Organic Impurities in Fine Aggregate

The organic impurities test results indicate that the fine aggregate used in this research did not contain high levels of organic compound that might otherwise harm the concrete. The suspension colors of three samples were all lighter than color #3 in the standard organic color plate. See Figure C.5, Appendix C for more details.

2.1.5 Percent of Attached Mortar

The #8 RCA contained mortar or paste attached to the original aggregate. Determining the percent of mortar attached is important because higher reclaimed mortar contents are associated with lower specific gravity, increased absorption and lower abrasion resistance of the RCA. The percent mortar was estimated using a method of point counting, similar to the procedure described in ASTM C 457. The results of this test indicate that, by volume, 28.9% of the RCA used in this study is old mortar, 68.5% is original aggregate and 2.6% is aged asphalt. Details of the process and results can be found in Table C.3, Appendix C.

2.1.6 Uncompacted Void Content of Coarse Aggregate

The test was performed in accordance with AASHTO T 326 (method A) to determine the loose uncompacted void content, U, of the coarse aggregate used. Results are shown in Table 2.2. According to AASHTO T 326 greater U-values indicate higher angularity, less sphericity, rougher surface texture or some combination of these three factors. Results indicate that the RCA was more rounded and spherical, and/or had a smoother surface texture than the natural quarried aggregates used (N1 and N2). Likewise, results suggest that this RCA was easier to compact than the

TABLE 2.1
Physical properties of aggregates used in this study

	Coarse aggregate					Fine aggregate
Aggregates properties	**#8 N1**	**#8 N2**	**#8 R**	**#11R**	**INDOT limit**	**#23 Natural sand**
Bulk specific gravity	2.69	2.62	2.30	2.33	—	2.56
Bulk specific gravity (SSD)	2.74	2.69	2.42	2.45	—	2.61
Apparent specific gravity	2.82	2.82	2.62	2.66	—	2.70
Absorption, %	1.8	2.7	5.3	5.4	5%, max	1.4
L.A. abrasion test (% mass loss)	29	31	36	34	40%, max	NA

NOTE: NA = not applicable. — = missing data.

TABLE 2.2
Uncompacted void of coarse aggregates

Aggregate	Uncompacted void of coarse aggregate (U)
#8 Dolomitic limestone 1 (N1)	49%
#8 Dolomitic limestone 2 (N1)	48%
#8 RCA (R)	44%

natural crushed quarried aggregate used, which may allow for slightly easier consolidation of the concrete mixture. Other researchers have reported similar values for crushed limestone and dolostone (48.2-51.2) and lower values for uncrushed gravel (42.2) (*19*), suggesting that the shape, angularity and texture of the RCA are between the values for a rounded river gravel and a crushed stone.

2.1.7. Ion Content Determination Results

The ion chromatography tests measured certain water soluble ions from the coarse aggregates used in this research. Results are presented in Table 2.3 and discussed below. Testing procedures are described in Appendix C.

The concentration of chloride ions in #8R leachate (851 ppm) was more than two times higher than that detected in leachates from #8N1 (377 ppm) and #8N2 (395 ppm). Higher chloride content in #8R's leachate was most likely the result of the application of chloride-based deicers when the source concrete for this aggregate was in service. The sulfate content in the leachate from #8R (39 ppm) was about one third of that of #8N1 (120 ppm) and #8N2 (106 ppm).

The potassium content in the leachates was determined by atomic absorption/emission spectrophotometry test. Test results indicated that the leachate from #8R has a relatively high potassium content (239 ppm), which is about 8 times higher than that observed in leachates from #8N1 (30 ppm) and #8N2 (32 ppm). Although it is impossible to determine the exact reasons for the increased levels of potassium ions, possible sources may be from potassium-rich deicers, if used, or from the hydrated and unhydrated cement present in the mortar attached to the surfaces of RCA particles. Aggregate #8N1 has similar potassium, chloride and sulfate ions contents to #8N2.

2.2 Concrete Test Results

Several tests were conducted on the fresh and hardened concrete to characterize its properties and estimate its performance and durability. Results are presented and discussed below and more details are provided in Appendix D.

2.2.1 Fresh Concrete Test Results

The slump and air content were measured within 15 minutes after the mixing process was completed. The density (unit weight) was also measured. The results are listed in Table 2.4 for both the laboratory and plant-batched mixtures.

During the laboratory trial batching, the w/cm, amounts of air entraining agent, and amounts and types of water reducers were varied in order to determine a combination that would best meet target values and meet INDOT's requirements for pavement concrete for w/cm ($\leq$0.45), slump (1.25–3.00 inches) and air content (5.7% to 8.9%). As shown in Table 2.4 all the laboratory and plant mixtures satisfied the target values for slump (1.25–3.00 inches) and air content specified by INDOT. All but one mixture, P-M2 met the w/cm requirement of $\leq$ 0.45.

The air content in fresh concrete was measured using both the pressure and volumetric methods. Results from these two methods were similar, and the differences between the two measurements ranged from 0.0%–0.75%, with an average difference of 0.27% over 18 mixtures. (See Appendix D and Figure D.2 more details).

2.2.2 Hardened Concrete Test Results

The mechanical properties and durability of the hardened concretes were evaluated in accordance with several different ASTM, AASHTO and INDOT standardized test procedures (as identified in Table 1.3). Test results are presented and discussed below and additional details can be found in Appendix D and reference (*15*).

2.2.2.1 Mechanical properties and density. The mechanical properties of concrete evaluated included: compressive strength, flexural strength, modulus of elasticity and Poisson's ratio. In addition, the air-dried density of concrete also was determined.

Compressive strength. The compressive strengths of 4×8 in. (100×200 mm) cylinders were measured in accordance with AASHTO T 22 after 3, 7, 14, 28, and 56 days of moist curing. The results are presented in Figure 2.1.

TABLE 2.3
Ion content of the coarse aggregate leachates

Type of coarse aggregate	Average of potassium ions concentration (ppm)	Average of chloride ions concentration (ppm)	Average of sulfate ions concentration (ppm)
#8 N1	30	377	120
#8 N2	32	395	106
#8 R	239	851	39

TABLE 2.4
Fresh concrete properties, w/cm ratio, and the dosage of admixtures used for lab (top) and plant (bottom) mixtures

LAB MIXTURES

Mixture designation	L-M1-1N1-C	L-M2-1R-C	L-M3-.3R.7N1-C	L-M4-.5R.5N2-F	L-M5-.3R.7N1-F	L-M6-.5R.5N2-C	L-M7-1R-F	L-M8-.3R.7N2-F	L-M9-1N2-F
Water reducer	2.5^1	2.5^3	5.5^1	1.5^2	1.5^2	3^1	3^1	1.5^2	1.5^2
w/c (w/cm)	0.42	0.42	0.42	0.42	0.42	0.44	0.42	0.42	0.42
Slump, in	3	3.2	2.4	3.3	2.3	2.75	3.2	3.8	2.9
Air entraining agent	0.9	0.5	0.8	0.5	0.5	1.0	1.5	0.6	0.7
Air content, pressure method	6.50	6.50	7.00	6.10	6.70	6.70	6.70	7.00	6.50
Air content, volumetric method	6.75	6.25	—	6.25	6.5	6.75	6.7	6.25	7
Density (lbs/ft^3)	144.9	139.6	143.6	141.5	142.4	140.2	135.3	140.8	142.8

Air entraining agent: fl oz/100 lbs cementitious.
Water reducer: [1]WRDA 20; [2]Glenium 3030 NS; [3]Mira 62 (mid-range water reducer); fl oz/100 lbs cementitious.

PLANT MIXTURES

Mixture designation	P-M1-1N1-C	P-M2-1R-C	P-M3-.3R.7N1-C	P-M4-.5R.5N2-F	P-M5-.3R.7N1-F	P-M6-.5R.5N2-C	P-M7-1R-F	P-M8-.3R.7N2-F	P-M9-1N2-F	P-M10-1N1-C
Water reducer	1.9	2.0	2.0	2.1	1.9	1.7	2.4	2.1	1.8	2.0
w/c (w/cm)	0.44	0.47	0.43	0.40	0.41	0.43	0.40	0.42	0.39	0.42
Slump, in	2.1	2.1	1.7	1.7	2.2	1.5	1.7	1.9	1.9	2
Air entraining agent	1.1	1.6	1.2	1.2	1.2	1.1	1.5	1.2	1.3	1.3
Air content, pressure method	6.6	6.7	6.5	6.6	6.5	6.8	6.4	6.4	6.3	6.7
Air content, volumetric method	6.1	6.5	6.3	6.2	6.5	7.0	7.0	7.0	7.0	6.75
Density (lbs/ft^3)	144.8	138	144.8	142.72	142.88	138.88	140	143.68	145.36	145.52

Air entraining agent: fl oz/100 lbs cementitious.
Water reducer: Glenium 3030 NS; fl oz/100 lbs cementitious.

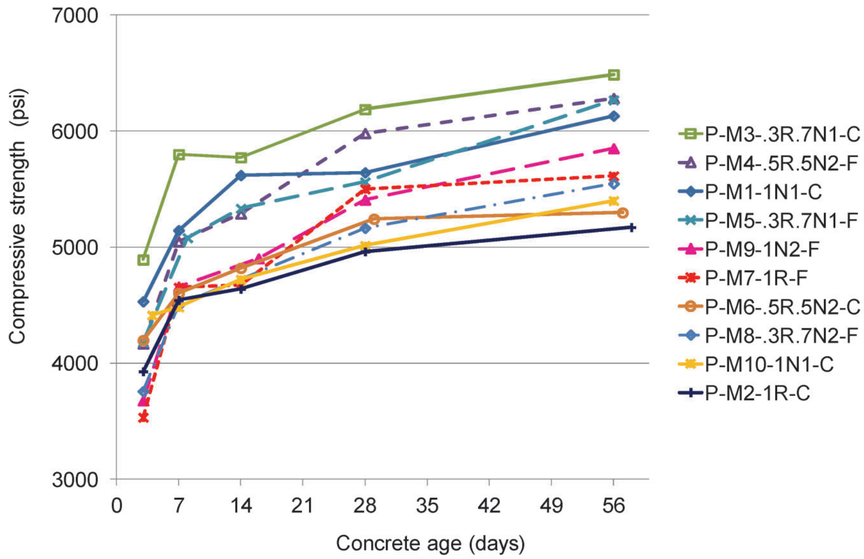


Figure 2.1 Compressive strengths of concretes mixtures at different ages.

The compressive strengths of all mixtures increased with age. The concrete mixture with 30% RCA (P-M3-.3R.7N1-C) had the highest compressive strength at all ages while the mixture with 100% RCA and no fly ash (P-M2-1R-C) had the lowest compressive strength at all ages beyond 7 days. It should be noted that the higher w/cm (0.47) of mixture P-M2 undoubtedly contributed to these lower strengths. The plain concrete mixture with 50% RCA (P-M6-.5R.5N2-C) had strengths similar to those of the control mixtures without RCA (P-M10-1N1-C).

For concrete with 30% RCA, the use of fly ash did not improve the compressive strength (compare P-M3 and P-M5). However, for concretes with 50% and 100% RCA, the use of fly ash in the mixture did improve the compressive strength after 7 or more days of moist curing. In fact, the use of fly ash improved the 50% RCA mixture (P-M4) so much that it achieved one of the highest strength values at later ages. The use of fly ash also improved the strength of the 100% RCA mixture (P-M7) to values similar to those obtained by the fly ash mixture without RCA (P-M9-1N2-F). Thus, the use of Class C fly ash improved the long-term compressive strength of concretes with RCA content higher than 30%. Despite the differences in strengths, all concrete mixtures developed strengths adequate for concrete pavement construction.

The properties of the natural coarse aggregates also affected the compressive strength, as shown by the results for P-M5-.3R.7N1-F that had compressive strengths approximately 10% higher than those of P-M8-.3R.7N2-F. (see also Figure D.4, Appendix D). Some of the increased strength for concrete made with N1 may be because of the tougher, denser and less porous properties of N1 compared to N2 (as shown in Table 2.1).

Flexural strength. Flexural strength tests were conducted in accordance with AASHTO T 97 and test results are summarized in Figure 2.2. Prismatic specimens, $6 \times 6 \times 21$ in. ($150 \times 150 \times 540$ mm), were tested after 3, 7, 28, and 56 days of moist curing.

All mixtures satisfied INDOT's minimum requirement for flexural strength at 7 days (570 psi [4.0 MPa]). The results for five of the mixtures (P-M1, P-M2, P-M3, P-M6 and P-M9) showed some irregular trends that may reflect the inhomogeneity of concrete, a difference in specimen moisture content, and/or a fluctuation in applied loading rate rather than actual variations in overall concrete strength.

The plain concrete with 50% and 100% RCA had lower flexural strengths than the plain concrete with 0% and 30% RCA, and the lowest strengths of all mixtures tested at 56 days. Fly ash contributed to the development of higher flexural strengths in concrete containing 50% and 100% RCA at later ages increasing the flexural strengths to levels that were similar to or higher than those of the control mixtures (as shown in Figure D.5, Appendix D). In fact, the mixture containing 100% RCA with fly ash (P-M7) had flexural strengths similar to those of fly ash mixtures with 0% RCA made with N2 (P-M9). (Additional discussions and plots can be found in Appendix D).

Modulus of elasticity and Poisson's ratio. The modulus of elasticity and Poisson's ratio were obtained by testing 4×8 in. (100×200 mm) cylindrical specimens after 28 days of moist curing in accordance to ASTM C 469. The test results are summarized in Figure 2.3.

As expected, aggregate appears to dominate the modulus of elasticity results, with the highest values associated with mixtures that contained N1 aggregate (both with and without fly ash). Comparing similar mixtures (all with fly ash), the use of N2 aggregate led to a significant (22%) decrease in modulus when compared to mixtures containing N1 (P-M 5 vs. P-M 8) and a slight (6%) increase compared to mixtures containing RCA (P-M9 vs. P-M7). In addition, there

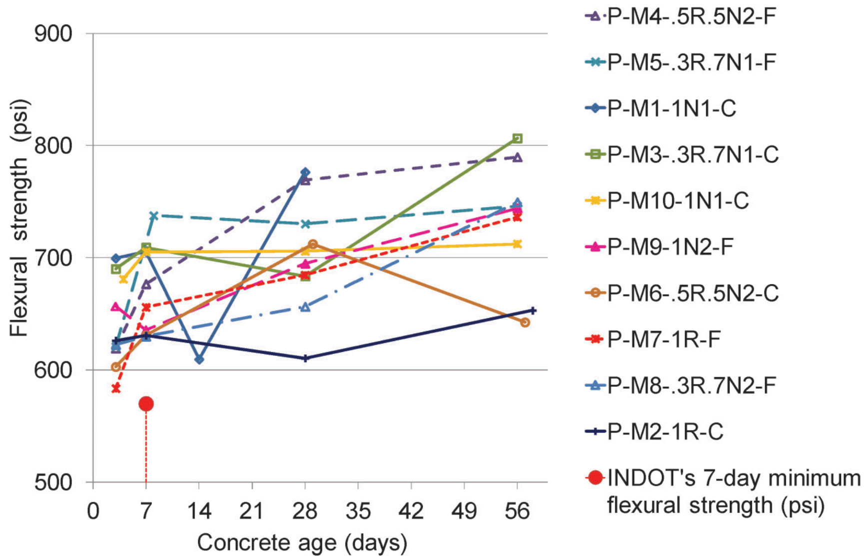


Figure 2.2 Flexural strength development for different concrete mixtures.

was a slight decreasing trend of the modulus as the amount of RCA increased in the fly ash mixtures (compare P-M9 to P-M8 to P-M4 to P-M7). Concrete mixtures with fly ash had 3%–9% higher modulus of elasticity than that of plain concrete at 50% RCA (P-M4 vs. P-M6) and 100% RCA (P-M7 vs. P-M2). At 30% RCA, the fly ash did not increase the modulus elasticity of the concrete (M5 vs. M3).

Overall, N1 mixtures had the highest modulus of elasticity, with the plain concrete with 30% RCA being the highest (P-M3). The plain concrete with 100% RCA (P-M7) had the lowest modulus of elasticity of all concretes tested. It can be noted that aggregate from source N1 had the highest density (bulk specific gravity) and the RCA had the lowest density of the aggregates used in this study. Therefore, the use of aggregate N1 appears to contribute to a stiffer concrete as seen as a higher modulus but also improved compressive strengths. The two control mixtures (P-M1 and P-M10) had comparable modulus of elasticity and Poisson's ratio even though their compressive strengths and flexural strengths were somewhat different. This supports the statement, that the modulus of elasticity for these mixtures was dominated by the aggregate properties.

As shown in Figure 2.3, the Poisson's ratio of mixtures with fly ash were generally lower than the Poisson's ratios for the same mixtures without fly ash. No specific correlations were found between the level of RCA replacement in the mixtures with the Poisson's

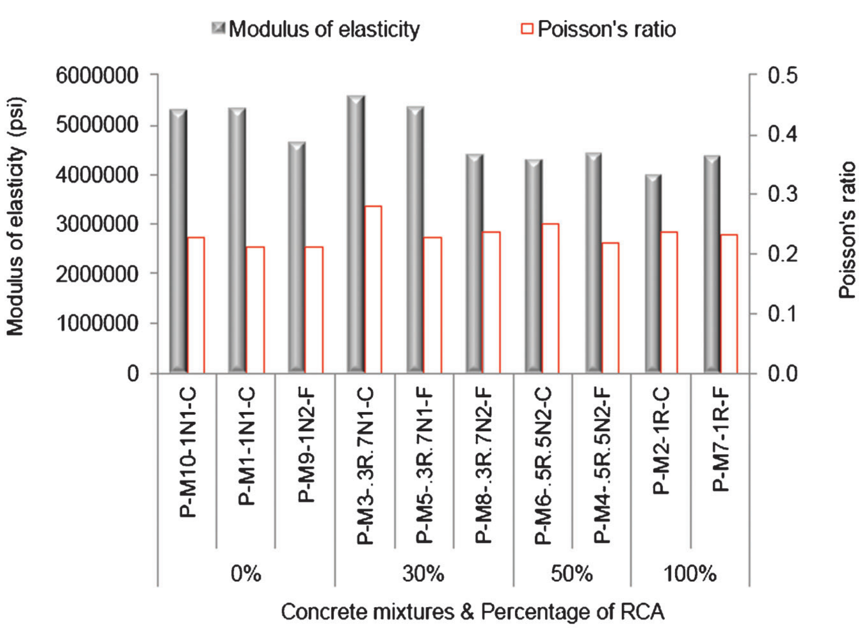


Figure 2.3 Modulus of elasticity and Poisson's ratio of concrete mixtures with different proportions of RCA.

ratio values for either plain or fly ash mixtures. INDOT does not have specific requirements for modulus of elasticity and Poisson's ratio for pavement concrete, but these values are considered in some levels of the MEPDG design and will influence the pavement design.

Density. RCA had a lower specific gravity than either of the natural aggregates used. As the percent RCA in concrete increased and the natural aggregate content decreased, the air-dry density of each concrete produced in the plant decreased (see Figure D.3, Appendix D). Additional details are available in Appendix D and reference (*15*).

2.2.2.2 Concrete durability properties. Several tests were conducted to evaluate the durability properties of the different concrete mixtures. These tests include rapid chloride permeability (RCP) test, rapid chloride migration (RCM) test, electrical impedance spectroscopy (EIS), drying shrinkage, water absorption tests, freeze/thaw test, length change measurement and scaling test (as shown in Table 1.3).

Rapid chloride permeability (RCP) test. ASTM C 1202 RCP tests were conducted on 28- and 56-day old wet-cured samples obtained from each plant mixture. The results are presented as 'charge passed in coulombs' (Figure 2.4 and Table D.1). Increased coulomb values correlates to increased potential for penetrability of chloride ions (Cl^-) into the concrete. All charges passed presented in this document have been adjusted for the "joule effect" that accounts for changes related to temperature variations of the solutions during the test (see Appendix D and reference (*15*) for more details).

For any given concrete mixtures, the charge passed at 56 days was about 7% to 44% lower than the charge passed at 28 days. Concretes with fly ash had 11% to 57% lower Cl^- penetrability at 56 days than plain concretes with similar RCA content, indicating the positive role of fly ash in reducing porosity. Comparing concrete with and without RCA, using 30% RCA in concrete did not significantly affect chloride ion penetration. Higher RCA contents (>50%) led to increased RCP values. These increased charges passed may reflect the increased contribution of conductive ions associated with RCA rather than indicating the actual difference in the concrete porosity (i.e., the value for leached chloride ions measured for RCA was 851 ppm, as compared to 395 ppm for N1 and 377 ppm for N2.).

The results of the RCP tests also were used to calculate the equivalent steady-state chloride diffusion coefficient from the Nernst-Plank equation. Details of the process and results are given in Appendix D.

An attempt to find a quicker and simpler way of determining the RCP test results was made in this study by predicting the final charge passed based on the measurements of the initial current at the time the charge was applied at the beginning of the RCP test. Results shown in Figure 2.5 indicate that there exists a strong linear relationship between predicted and actual passing charge for plain concrete mixtures, but clearly this procedure will not be acceptable for use with fly ash mixtures, as indicated by a very low value $R^2 = 0.19$.

Another approach to predicting the total charge passed based on the initial current was examined by

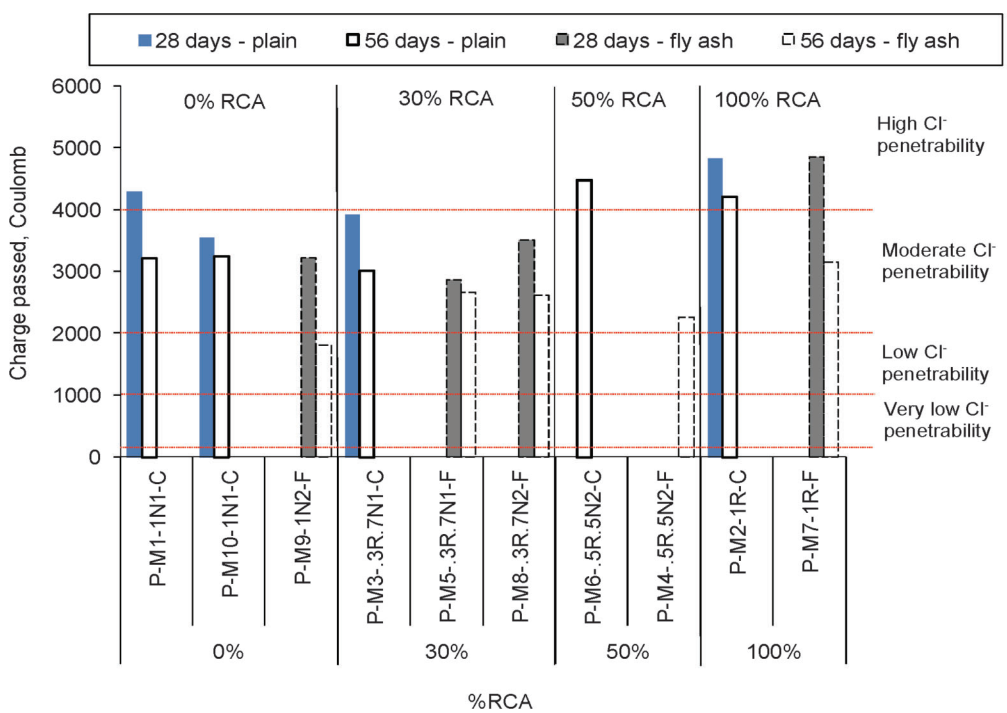


Figure 2.4 Average RCP charge passed for concretes with different % RCA.

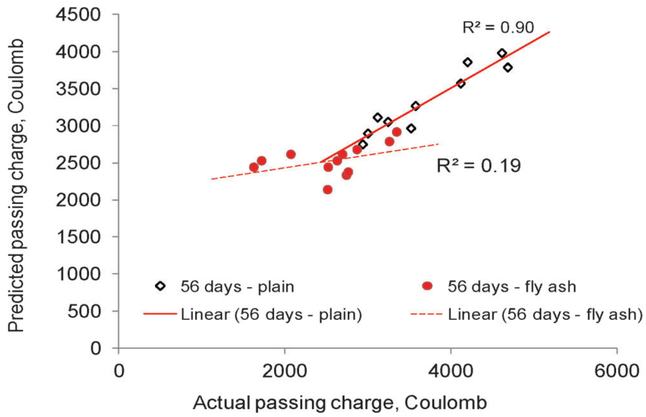


Figure 2.5 Calculated (predicted) charge passed vs. actual (measured) charge passed for 56 days old concretes (plain and fly ash).

finding the correlation between final charge passed and theoretical bulk resistance (R). As shown in Figure 2.6 the relationship between bulk resistance and charge passed from RCP test results is nearly linear. These results suggest that the RCP six-hour cumulative charge measurement may be predicted using quick early measurements of the initial current. The equations used for calculations and additional details are discussed in Appendix D.

Rapid chloride migration (RCM) as per NT Build 492. The RCM test performed in this study was similar to the RCP test but required a lower applied potential over a longer (24-hour) period and visual examination of the actual Cl^- penetration. This test was performed using the NT Build 492 specification (*21*). From these results the non-steady-state migration coefficient (D_{nssm}) was calculated. Based on the value of non-steady-state migration coefficient (D_{nssm}), only plain concrete with 50% RCA was classified as not suitable for aggressive environment ($D_{nssm} > 16.10^{-12}$ m^2/s). All others concretes had moderate resistance to chloride ion penetration ($8x10^{-12}$ $m^2/s < D_{nssm} <$ $16x10^{-12}$ m^2/s). The fly ash concretes generally had improved chloride ion penetrability resistance (lower D_{nssm}) compared to similar mixtures without fly ash, except for concrete with 100% RCA. The procedures, results and additional discussion of the RCM test are available in Appendix D and Table D.5.

Electrical impedance spectroscopy (EIS) & surface resistivity. Based on the EIS test results, the resistivity of concrete generally decreased with increased amounts of RCA in the concrete. Concrete with fly ash generally had improved resistivity over that of plain concrete, especially at later ages (see Figure 2.7). The EIS results predicted similar behavior as the RCP test, with a correlations between test results having a trend line with an R^2 value of 0.763 (Figure D.7, Appendix D).

In this research, surface resistivity tests also were conducted to estimate the concrete's resistivity. The EIS 56-day results predicted behavior similar to that predicted by surface resistivity test for all plain concrete samples (ages 56-176) and for fly ash samples that were of similar ages (56-69 days) to the EIS sample. Two of the five fly ash concrete samples that were older (126 and 156 days old) with 30% and 50% RCA, showed significantly higher surface resistivity compared to all other surface resistivity and 56-day EIS specimens. A similar increase was not seen for older specimens without fly ash (see Table D.6 and Figure D.8, Appendix D).

Additional data and discussions are presented in Appendix D and the results of the RCP, RCM, EIS and surface resistivity tests are summarized in Table D.5 in Appendix D.

Total drying shrinkage. The shrinkage test results are presented in Figure 2.8. In general, the shrinkage of concrete with RCA tended to be higher than that of concrete with N1 natural aggregate, especially at 100% RCA replacement levels (consider mixtures P-M7 and P-M2). However the shrinkage of concrete made with 100% natural aggregate N2 (P-M9) was very comparable to or higher than the shrinkage of RCA concrete with up to 50% RCA (P-M3, P-M4 P-M5 and P-M8). Comparing the shrinkage of mixture P-M3 with the shrinkage of mixture P-M5 (similar mixtures with and without fly ash), it can be seen that the fly ash mixture shrunk more, suggesting that the use of fly ash also increased the drying shrinkage. For concretes with 100% RCA, the total drying shrinkage exceeded the

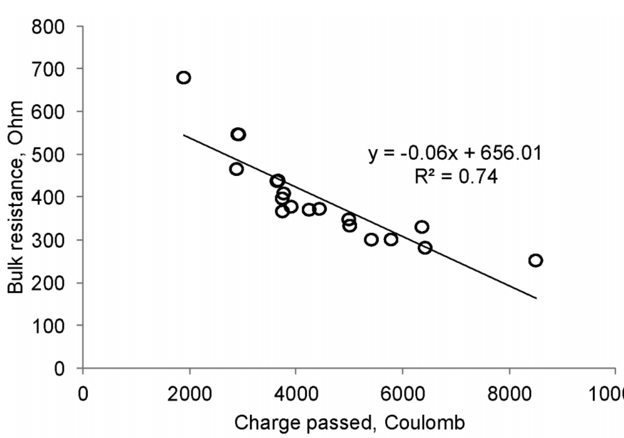


Figure 2.6 Relationship between charge passed and bulk resistance of concrete based on RCP test results.

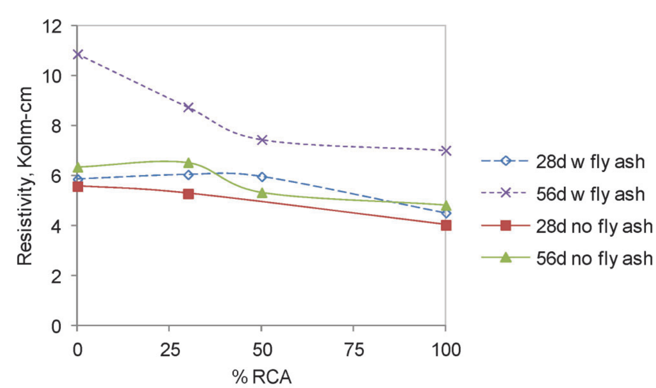


Figure 2.7 EIS results of resistivity compared to % RCA.

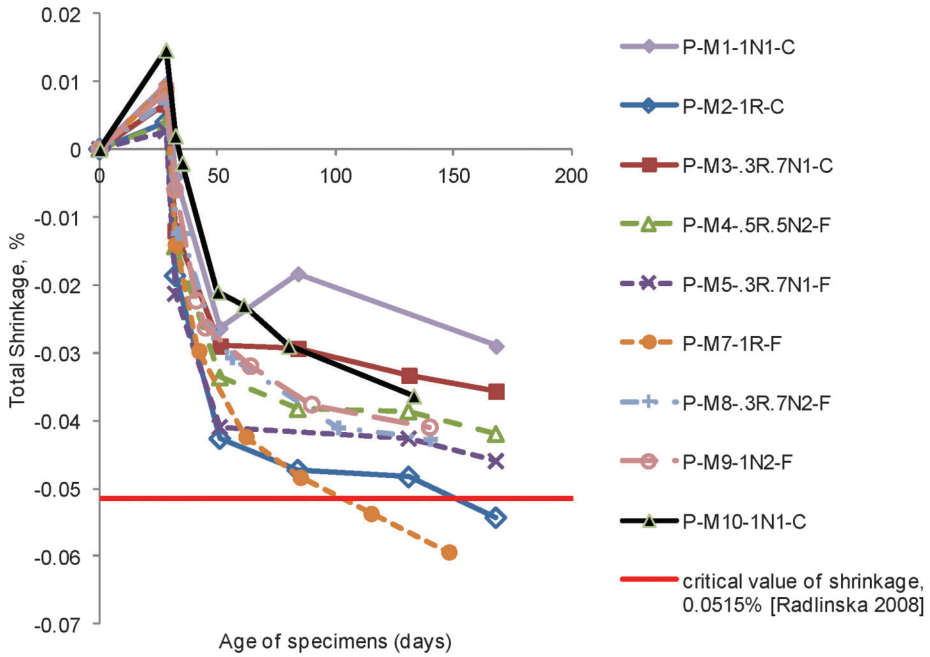


Figure 2.8 Total shrinkage of concrete mixtures.

critical limit of -0.05% after 100 and 150 days with the use of fly ash (mixtures P-M7_1R-F and P-M2_1R-C respectively).

Water absorption. The results of the water absorption test (based on ASTM C 1585) for concrete from nine different mixtures are shown in Figure 2.9, and the average absorption rates are given in Table 2.5.

Although key factors such as age and w/cm are not consistent between samples some general trends can be observed which suggest that concrete with fly ash had lower absorption rates compared to the comparable mixtures without flyash (except for mixture P-M9). The absorption rates for concrete containing RCA fell within the range of absorption rates found in concretes made with the two natural aggregates (P-M9 and P-M10). In fact, concrete containing 30% and 50% RCA and fly ash had the lowest absorption rates of all concrete tested. Caution is suggested in interpreting these results as the short conditioning period of the samples has been reported to generate a wide range of relative humidity values, which influences the test results (detail can be found in reference (*20*)).

Freezing and thawing. The concrete from all 10 plant-batched mixtures showed good freezing and

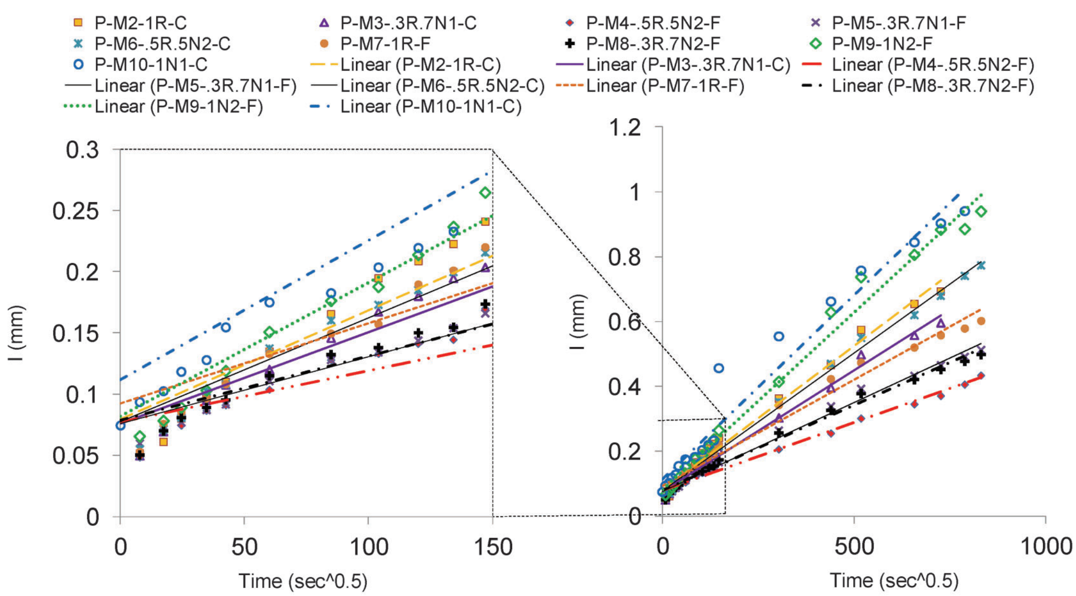


Figure 2.9 Water absorption test results on concretes from different plant-produced mixtures.

TABLE 2.5
Water absorption test results on concretes from different plant-produced mixtures*

% RCA	Mixture designations	Initial absorption rate ($mm/s^{0.5}$)	Secondary absorption rate ($mm/s^{0.5}$)	Age of sample, days	w/cm
0%	P-M10-1N1-C	0.0011	0.0009	56	0.42
0%	***P-M9-1N2-F***	***0.0014***	***0.0009***	***70***	***0.39***
30%	P-M3-.3R.7N1-C	0.0011	0.0007	100	0.43
30%	***P-M5-.3R.7N1-F***	***0.0007***	***0.0005***	***148***	***0.41***
30%	***P-M8-.3R.7N2-F***	***0.0008***	***0.0004***	***77***	***0.42***
50%	P-M6-.5R.5N2-C	0.0011	0.0008	127	0.43
50%	***P-M4-.5R.5N2-F***	***0.0007***	***0.0004***	***177***	***0.40***
100%	P-M2-1R-C	0.0014	0.0008	102	0.47
100%	***P-M7-1R-F***	***0.0011***	***0.0005***	***91***	***0.40***

NOTE: Fly ash mixtures are identified in ***boldface italics***.

thawing (F/T) durability based on AASHTO T 161 Procedure A. All concretes had relative dynamic modulus of elasticity (RDME) values above 90% after being subjected to up to 350 freezing and thawing cycles, which corresponds to durability factors (DF) >90 (as shown in Figure 2.10).

INDOT specifies that the expansion of F/T beams should not exceed 0.06% to qualify a given aggregate as AP aggregate for acceptable use in concrete pavements. Unfortunately, the comparator was damaged during the testing of the first five mixtures (P-M1, P-M2, P-M3, P-M4, and P-M5) and the length change measurements collected are invalid (showing unrealistic values, for example $\pm$1.2% expansion for a known high-quality AP aggregate and no evidence of cracking in the beams). However the length change results for other beams (M-6, M-7, M-8, M-9 and M-10) with 0% to 100% RCA all had expansions of 0.03% or lower satisfying the INDOT requirement for AP quality aggregate and correlating well with high durability factors (see Figure D.9, Appendix D).

Scaling. Specimens fabricated from each of the 10 different plant-produced mixtures were exposed to 50 cycles of freezing and thawing while ponded with 4% calcium chloride ($CaCl_2$) solution. Based on visual observations of the surfaces of the concrete specimens, it appears that all concrete experienced very light scaling. The scaling manifested itself as the loss of thin layers of paste (mortar) from small areas on the surfaces of the specimens. However, there was not a single specimen for which this surface scaling exposed coarse aggregate particles. Following the guidelines given in ASTM C 672 *Standard Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals* the surface conditions of all specimens were rated "1"- very light scaling, as it is shown in Figure 2.11.

More detailed scaling results and data are available in reference (*15*).

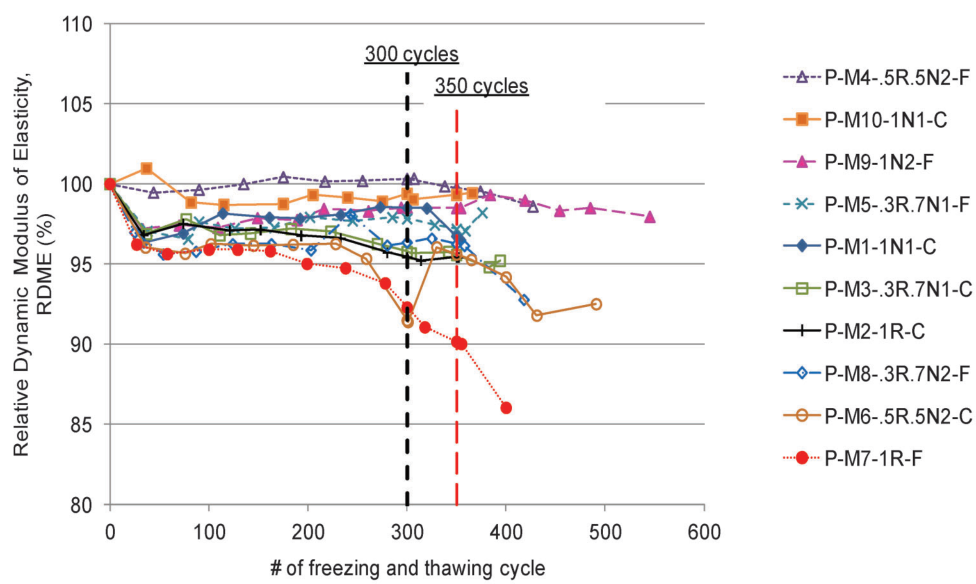


Figure 2.10 Changes in relative dynamic modulus of elasticity (RDME) for plant mixture concretes when subjected to freezing and thawing cycles.

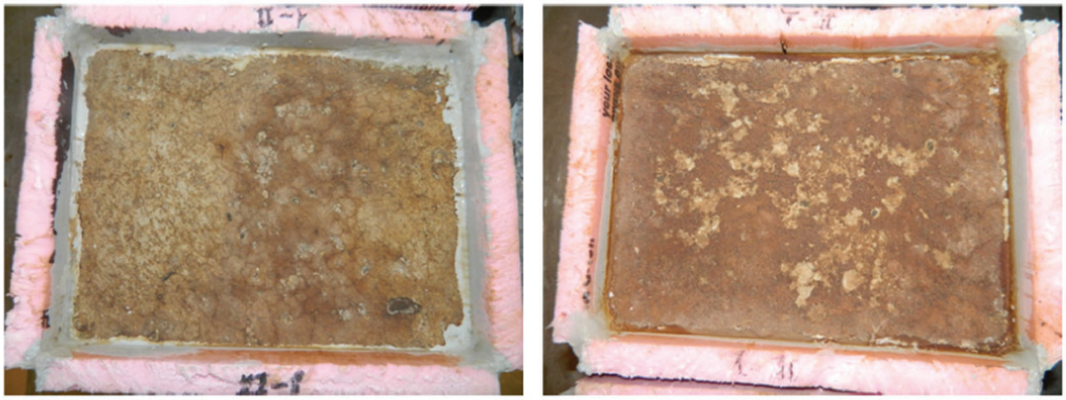


Figure 2.11 Scaling of P-M2-1R-C subjected to 4% $CaCl_2$ after 50 cycles.

3. CONCRETE WITH MODIFIED AGGREGATE GRADATION

3.1 Background

The aggregate gradation of a mixture affects both plastic and hardened concrete properties (*18*). Controlling and modifying the amount of aggregate on each sieve can lead to better aggregate packing, and, if proportioned appropriately, can contribute to increased workability and durability without increasing water or cement content (*18*), as well as lead to reduced cementitious usage and more economical mixtures. As shown in Section 2.1.1 and Appendix C, all combined gradations were classified as sandy, and none of the combined gradations fell entirely within the 8-18 band.

The purpose of modifying the aggregate gradation in this study was to evaluate the effects of such modifications on selected concrete properties in an attempt to investigate whether 1) a more continuous particle size distribution could improve hardened concrete properties, 2) an increased workability could be achieved to compensate for the effect that the increased absorption by the aggregate may have on the mix, and 3) RCA produced from sources other than pavements can be used successfully in a concrete paving mixture. The effects of modified gradations were evaluated by changing the ratio of fine-to-coarse aggregates (from 47% to 43%, based on mass) and by adding a mid-sized aggregate (#11's with d_{max}=0.5 in) to the mixtures. Reith-Riley Company produced the #11R recycled aggregate from piles of mixed-use concrete waste. In this portion of the project, the natural aggregates previously described and used in the plant mixtures were combined with #11 aggregates listed in Table 1.1.

3.2 Concrete Properties

A total of three modified gradations were used in this study to prepare six lab batch mixtures. The slump and air content were measured, and two flexural beams and nine 4x8 cylinders were cast from each mixture. The details of the mixtures with modified gradations are presented in Table E.1, Appendix E.

3.2.1 Plastic Properties

The target air (5.7%–8.9%) and slump (1.25–3.00 in) values were met in all but one mixture (O-M1 slump = 3.3 in), as shown in Table E.2. Due to the variations in w/cm, amount of water reducer and air-entraining agent used, and the batching process (lab vs. plant), the direct influence of the type of aggregate and its gradations on the slump and air content cannot be clearly assessed. However, in some of the mixtures with a modified gradation, the workability (slump) remained constant or increased, even though the w/cm and/or amounts of WR were reduced (see the details in Appendix E, Table E.3).

3.2.2 Flexural Strength

The 7-day flexural strengths of concrete made with modified aggregate gradations were compared to the flexural strengths of the concretes with non-modified gradations batched in the plant and in the lab (see Figure E.2, Appendix E). The plain concrete with modified gradation and no RCA (O-M6) had the highest 7-day flexural strength value of all mixtures used in this study (740 psi), approximately 9% to 17% higher than that of the other control mixtures (P-M1 and P-M10). For modified gradation mixture concretes with 30% and 55% RCA, the average 7-day flexural strengths were very comparable, varying only 1 to 7 percent, to the average flexural strengths of other concretes with 30% and 50% RCA (consider O-M2 vs. P-M3 and L-M3; O-M1 vs. P-M6 and L-M6; and O-M5 vs. P-M4 and L-M4).

Compared to the non-modified gradation plant and lab mixtures with 100% RCA, modified gradation concretes with 100% RCA had 13%–18% lower 7-day flexural strengths (P-M2 vs. O-M4; and P-M7 and L-M7 vs. O-M3). In addition, the 7-day flexural strengths of these concretes (O-M3 and O-M4) were lower than

INDOT's minimum requirement for 7-day flexural strength (570 psi). Based on the results obtained, it can be stated that the use of modified (more continuous) gradation increased (up to 17%) the 7-day flexural strength of the control concrete (made with 100% natural aggregate), but did not improve the 7-day flexural strength of the RCA concrete. This may relate more to the quality of the #11R and the quality of concrete from which #11R was crushed than the gradation used.

3.2.3 Compressive Strength

The 7-day and 28-day compressive strength results for modified and non-modified (plant) mixtures are presented in Appendix E, Figures E.3 and E.4. The results indicate that concretes with modified gradations had slightly lower compressive strength than the concrete with non-modified gradation (less than 15% difference). Fly ash did not seem to affect the compressive strength of concrete with the modified gradation since the 28-day compressive strength results of modified concrete with and without fly ash are comparable (O-M1 vs. O-M5 and O-M4 vs. O-M3 had only 1%–3% differences).

3.2.4 Rapid Chloride Permeability

The results of the average charge passed obtained during the rapid chloride permeability (RCP) test for non-modified (plant) and modified aggregate gradation mixtures are shown in Figure E.5, Appendix E. Four out of six mixtures with modified gradation (0% and 55% RCA without fly ash, and 55% and 100% RCA with fly ash) had slightly lower coulomb values compared to the corresponding plant mixtures (7%–24% lower) indicating a slightly better resistance to chloride ion penetration. These results contradict the RCP results from the other two mixtures with a modified gradation (30R-C and 100R-C) in which their coulomb values were approximately 28%–38% higher than those measured for the corresponding plant concretes. Therefore, no relationship was clearly identified that consistently related the modified gradation to the resistance to chloride ion penetration. As seen with the plant mixtures, the use of fly ash significantly reduced the charge passed compared to similar concrete mixtures without fly ash (49%–57%).

4. BENEFIT-COST ANALYSIS OF USING RCA IN NEW CONCRETE PAVEMENTS

4.1. Background

As the infrastructure continues to age and concrete structures are replaced, the availability of concrete waste to be crushed into RCA is expected to remain steady, if not increase. This project has demonstrated that RCA made from INDOT concrete pavements can be used successfully in new concrete pavements as a replacement for natural coarse aggregate. Putting RCA back into the pavement structure, either as base material or in the concrete mixture is a much more sustainable practice then treating it as waste. Some agencies already have implemented zero-waste practices of reusing all materials generated from reconstruction projects back into the new structure.

In order to determine the cost-effectiveness of crushing and reusing concrete pavements as aggregate in new concrete pavements, the following analysis was developed. Although this project did not address the feasibility of using RCA in the base layers, that option was included in the BCA model.

4.2. Benefit-Cost Analysis (BCA) Model

In order to provide the user with flexibility and ease of updating as needed, the Benefit-Cost analysis model was developed as an Excel spreadsheet (see Appendix F). This model is able to consider the use of RCA as coarse aggregate for new concrete and/or as base material (#8 and/or #53). This model also includes the ability to estimate the amount and cost of RCA that could be produced from an existing concrete pavement.

4.2.1. Input Parameters

Most of the input parameters for this cost benefit analysis are not static and are expected to change either with each project or over time. To give the engineer and other decision-makers the flexibility of using this analysis for a variety of situations most of the fields are not fixed, but have been developed to require input values from the user. Many of these inputs are unique to each project, such as hauling distances and amount of aggregate needed, while other inputs may be common for many different projects, such as landfill costs or new aggregate cost, but are likely to change periodically.

Figure 4.1 outlines the input fields used in this model and provides an example of typical pavement structural inputs. The cells highlighted in yellow are required project-specific information. Cells highlighted in blue indicate values that are calculated by the model from the user inputs.

As shown in Figure 4.1 the spreadsheet calculates how much total aggregate is needed for the project, how much RCA will be needed and how much RCA will be available from the old concrete pavement (PCCP). All of these values are calculated based on the user's inputs of how much of the coarse aggregate in the concrete mixture will be RCA, how much (if any) will be used for the base and the dimensions and extent of both the old PCCP and the new pavement being built. The variability in the efficiency of the crushing operation also is considered when calculating the amount of RCA that may be produced from an old structure. The percent of the concrete structure that becomes RCA depends on the aggregate gradation being produced, the crusher being used and other aggregate production variables. In the production of #8 aggregate, a value of

RCA Production Efficiency	% of PCCP => RCA		#8	#53	% waste*	#8	#53
			50%	60%		50%	40%
Concrete mixture design (lbs/cyd)	Cement	Fly ash	Water	Coarse agg.	RCA	Fine agg.	w/cm
	611	0	256.62	849	749	1348	0.42
% RCA (by mass)	47%						

data input
data calculated

Structural Design of New Pavement	Driving Lanes				PCC Shoulder	Area of Pavement (sq. ft)	Total volume (cyd)	Estimated qty. required (US tons)			%RCA in new project by mass	Estimated RCA needed (US tons)
	No.	Width (ft)	Thickness (in)	PCCP Length (mi)	Width (ft)			Fine Agg	CA #8	CA #53		
Concrete	3	12	10	1	4	211,200	6,519	4,393	5,208		47%	2441
Base course #8's (1.5 ton /cyd)	3	12	3	1	4	211,200	1,956		2,933		100%	2933
Base course #53's (1.4 ton/cyd)	3	12	6	1	4	211,200	3,911			5,476	100%	5,476
Total estimated qty. required (US tons)								4,393	8,142	5,476		10,850
PCC Pavement Being Crushed	2	12	14	2	0	253,440	10,951					

*Percentage of the PCCP that is produced into RCA (i.e., 70% = 70% of existing PCCP become RCA and 30% is waste).

Figure 4.1 Pavement structural inputs fields.

50% of the total mass of concrete removed becoming RCA is not unreasonable, but it is possible for this efficiency to be improved.

The example given in Figure 4.1 is not meant to represent any particular project, but many of the values are similar to the INDOT field trial placement on the shoulder of US 231 in West Lafayette, IN (as described in Chapter 8). Other assumptions behind the calculations used in this section of model include the following assumed densities:

1. PCCP is 2 tons/cubic yard (t/cyd)
2. Broken PCCP slabs = 1.75 t/cyd
3. #8 RCA is 1.5 t/cyd
4. #53 RCA is 1.4 t/cyd

The cost of removal of the old PCCP is not considered in this example because that cost will be incurred whether the concrete is crushed for RCA or not. If a situation occurs in which any one of these assumption are no longer valid then the user must adjust the calculations in the relevant cell(s) of the spreadsheet.

Figure 4.2 is a continuation of the BCA spreadsheet input requirements that includes costs of hauling the old PCCP to the crushing operation or to the landfill; the cost of hauling the RCA from the production site to the concrete batch plant; and the cost of hauling the natural aggregate from the quarry/production plant to the concrete batch plant. It is assumed that the cost of hauling concrete from the batch plant to the construction site will be the same whether RCA is used or not, so this cost is not considered here.

The section of the spreadsheet shown in Figure 4.2 also allows for user input for crushing costs. Crushing costs and hauling costs will vary and may depend on

	Crushing Costs	Hauling Costs	Landfill Costs	Haul Distance Between: Old Project & Crushing Operation	Crushing & Delivery Pt	Project & Landfill	Nat'l Agg Source & Delivery Pt	Cost of Natural Agg
	$/ton	$/ton/mi	$/ton	(mi)	(mi)	(mi)	(mi)	$/ton
Concrete	5	0.35	2	10	7.4	50	21	9.5
Base course #8's					7.4		21	9.5
Base course #53's					7.4		21	9
	$5/ton at plant or $4/ton on grade+cost of mobilization	Typically $0.30-0.40 /ton	typically $1/ton	Assume Disposal of 50% of the RCA (fines) the same for all scenarios			#8 typically $8.50 to $10.50/ton	

Figure 4.2 Additional input parameters—aggregate and hauling related costs.

whether the crusher is brought to the construction site and a separate mobilization fee is charged, or the crushing operation is off-site at an established crushing operation. Estimates are given based are current cost estimates suggested by industry, but costs may vary greatly depending on several variables such as the location of the construction relative to a crushing facility; availability of mobile crushing operations and mobilization costs; amount of material being crushed; and the producer's equipment and experience to name a few. The more old concrete there is to remove and crush the more efficient an on-site crusher becomes since mobilization of equipment is often a large portion of the expense. Some typical crushing costs are provided in Figure 4.2 for the user's convenience in case project specific costs are not available.

As noted previously, the yellow cells shown in Figure 4.2 are required user inputs that are based on project-specific information, and standard values are available for input into the green cells if project-specific information is not available. Cells highlighted in green are necessary inputs for which standard suggested values are available if project-specific values are not available. Assumptions and input explanations are given in the bottom row of Figure 4.2.

4.2.2. Output Values

An example of all the final output values from this BCA is provided in Figures 4.3 and 4.4. The inputs given in Figures 4.1 and 4.2 were run through the model to provide the final outputs shown in Figures 4.3 and 4.4. As previously noted, all blue cells indicate fields that are calculated based on user inputs. The breakdown of unit costs is provided in Figure 4.4.

The example given in these series of tables represents a hypothetical INDOT project completed in the Lafayette area using Delphi Limestone natural aggregate, the RCA being produced by a local aggregate producer by removing and crushing a nearby INDOT pavement and concrete waste having to be hauled to a facility north of Indianapolis.

4.3. Cost Savings Realized

The outputs given in Figures 4.3 and 4.4 are taken from the BCA spreadsheet using the inputs given in Figures 4.1 and 4.2. In this example, RCA replaced approximately 50% by volume (47% by mass) of the coarse aggregate in a concrete paving mixture used to pave one mile of a 3-lane highway with concrete shoulders. The cost savings realized using #8 RCA at this level of replacement in the concrete mixture is $2.26 per ton of RCA, for a project-wide savings of $5,517, assuming landfill costs are not a factor. If RCA also is used for 100% of the base material, then an additional savings of $22,658 is realized, for a project-wide savings of $28,172.

If landfill costs are a factor and the old PCCP is brought to a waste facility instead of used to produce RCA, the cost difference is dramatic. In the given scenario, producing #8 RCA reduces the generated waste by 50% and producing #53 RCA reduces the generated waste to 40% of the original mass. Also in this scenario, the old PCCP is used to produce RCA for 100% of the base material and 50% of the coarse aggregate in the new concrete pavement. Therefore, the only waste is the fine material produced as a by-product of RCA production (which could be used in other applications not considered here). The cost of landfilling these fines only, compared to landfilling all of the

Costs for Given Mix Design						Cost for 0% RCA			Cost Savings Using RCA		Structural layer
Crush RCA:	RCA Haul (rd trip)	Total Cost of RCA	Natural aggregate delivered	Landfill RCA waste	TOTAL	Natural aggregate delivered	Landfill 100% PCCP	Total			
$	$	$	$	$	$	$	$	$	w/o landfill costs	Including landfill costs	
12,206	23,411	35,617	46,626	47,603	129,846	87,760	427,093	514,853	5,517	385,007	Concrete
14,667	28,131	42,797	0	57,200	99,997	49,427		49,427	6,629	376,523	Base course
27,378	46,122	73,500	0	71,182	144,682	89,525		89,525	16,025	459,696	Base course
TOTAL		151,914	46,626	175,985	374,526			653,805	28,172	279,280	TOTAL
Total Agg Cost (including base)		198,540				226,712					
Agg Cost PCCP only		82,243				87,760					
Agg Cost for Base		116,298				138,952					
Agg Cost of #53		73,500				89,525					

Figure 4.3 Example of BCA output.

Cost per Ton ($) (Without Landfill Costs)		
Cost per Ton ($)	#8	#53
RCA Hauling	9.59	8.42
RCA Crushing	5.00	5.00
RCA Delivered	*14.59*	*13.42*
Natural Aggregate Hauling	7.35	7.35
Natural Aggregate	9.50	9.00
Natural Aggregate Delivered	*16.85*	*16.35*
Net Cost Savings Using RCA	**2.26**	**2.93**

Figure 4.4 Breakdown of unit costs in Figure 4.3 example.

old PCCP if no RCA was produced, leads to a savings in landfill costs of $279,280. Combining the cost savings realized by partial replacement of the natural aggregate with RCA ($28,172) with the savings in landfill costs ($279,280) the total project-wide savings of $307,452 would be realized for this hypothetical 3-lane mile-long project.

4.4. Land Filling of Old Concrete

Although a modest $2/ton landfill costs is used in this BCA based on a web-search and an assumption that a project this size may receive a bulk discount, the actual landfill cost may be quite a bit higher. As shown in Figure 4.5, one waste facility near Indianapolis advertised a cost of $7/cyd for disposal of clean demolition waste (facility name intentionally removed). A cost of $7/cyd equals approximate $4.60/ton (including solid waste fee) which demonstrates that landfill costs higher than estimated in this example are possible.

The landfill cost estimates in this report are low compared costs across the nation, and most likely only will increase with time. The National Solid Wastes Management Association reports that tipping fees increased from an average of $8/ton in 1985 to $34.29/ton in 2004, with averages as high as $70.53/ton in the Northeast region (*22*).

Awareness has increased over recent years of the re-usability of old concrete and of the negative environmental impact of landfilling construction debris. However there is still an estimated 517,260 tons of demolition and construction debris entering Indiana landfills yearly (approximately 6% of the landfill waste) (*23*).

According to the www.in.gov website, only 20 of the 92 counties in Indiana have a facility that accepts construction and demolition debris. This low distribution of facilities suggests that if any portion of old concrete pavements need to be landfilled, a significant haul distance is possible and related costs incurred.

4.5. Summary of Benefit-Cost Analysis

This BCA is a useful tool in estimating the savings that can (or cannot) be realized by recycling old concrete pavement into new aggregate. With proper inputs this model can provide an estimate of how much RCA can be expected from the removal of an existing pavement, cost comparisons between using RCA verses natural aggregate for a particular project and cost comparisons between using the RCA in the concrete mixture and/or in the base structure. The example given is just one possibility of hundreds of options that may exist in a given construction season. Cost comparisons of different options for a single construction project can be examined quickly and easily using this BCA spreadsheet, aiding the engineer in making an informed decision leading to a wise use of resources and potential cost savings.

5. SUMMARY AND CONCLUSIONS

The RCA used in this study met all INDOT specifications for #8 AP-quality aggregate for concrete paving, except for the percent absorption, which was slightly above the 5% maximum (5.3%). The lower specific gravity of the RCA led to lower unit weights of the concrete containing RCA.

All the concrete mixtures produced in a ready-mixed plant satisfied INDOT's PCCP requirements for slump (1.25–3.00 in), air content of fresh concrete (5.7%–8.9%) and minimum 7-day flexural strength (570 psi). RCA decreased concrete's workability, especially for concrete mixtures without fly ash, however all concrete satisfied the maximum w/cm 0.45 requirement except for the 100% RCA mixture without fly ash (0.47 w/cm). The adjustments to the w/cm, air entraining agent and water reducer contributed towards achieving the target slump and air content values, and most likely further adjustments with admixtures could have reduced the w/cm of the 100% RCA to within specification limits in this study. Both the pressure and volumetric methods of air content measurement yielded comparable sets of results. It therefore appears that the pressure method may be used reliably for concrete with RCA, thus simplifying the task of air content determination.

Similar to concrete with all natural aggregates, generally the mechanical properties of the RCA concretes improved with age. Concrete with 30% RCA without fly ash achieved tested values of compressive strength, 7-day flexural strengths, elastic modulus and Poisson's ratio equivalent to or better than the control mixture. When the percentages of

XXXX- Indianapolis
Clean Fill - $7.00 per Cubic Yard (uncontaminated rocks, brick, concrete, road demolition waste materials, or dirt) all Solid Waste materials disposed of at XXX Landfill will be assessed mandatory state solid waste fees of $0.60 per ton.

Figure 4.5 Advertised costs for facility accepting demolition waste near Indianapolis.

RCA in plain concrete mixtures increased to 50% and 100% levels, the mechanical properties tested at 56 days decreased, when compared to the control concrete (plain, 0% RCA). By substituting Class C fly ash for approximately 20% (by mass) of the cement, this reduction of the mechanical properties was eliminated. In fact, the use of fly ash resulted in improved mechanical properties of concrete with 50% and 100% RCA compared to plain concrete with the same percentages of RCA (up to 23% and 25%, respectively). The lower specific gravity of #8 RCA (2.42) contributed to lower densities of the concrete (up to 5.4% lower for concrete containing 100% RCA).

In terms of durability properties, the freeze-thaw durability of all concretes was very good with DF> 90 at 350 cycles and scaling tests resulting in only very light scaling for all concretes (rated as 1). The concrete's resistance to chloride ion penetration decreased in plain concretes with higher RCA contents. At 30% RCA the resistance of concrete was similar to the resistance of the control concrete with 0% RCA. However, at 50% and 100% RCA the concrete's resistance to chloride ion penetration decreased most likely due to the more porous matrix of RCA than natural aggregates and the higher ionic species content in RCA. The use of fly ash improved the chloride resistance of all concretes such that the 56-day measurements were similar to or better than that of the control mixture. Therefore, these tests showed that the durability of RCA concrete can be improved by using fly ash as a partial replacement of cement.

Results from the RCP testing suggest that predicting the final current values based on the initial current is valid for plain concretes ($R^2 = 0.90$) but not for concretes containing fly ash ($R^2 = 0.19$). Comparing RCP results with surface resistivity test results suggests there is a good correlation between these test results for plain concrete, but the results for fly ash concrete at different ages do not correlate well.

Six mixtures were tested in which the aggregate gradation was modified to contain a certain amount of #11 (mid-size) aggregates. Results indicated that these modified gradations increased the 7-day flexural strength by 9%–17% for the control concrete with all natural aggregate, but did not improve the strengths of any of the concretes containing RCA. In fact, strengths for some mixtures were significantly reduced, especially those with more than 50% RCA. The quality and types of the original concrete from which #11R was made may have contributed to these reduced strengths.

Comparing the resistance to chloride ion penetration (RCP) in concretes with a modified gradation to similar non-modified gradations, the resistance improved slightly in four concrete mixtures but worsened significantly in two other mixtures. This implies that there is no significant effect of modified gradation on RCP results. Class C fly ash reduced the permeability of RCA concrete with modified gradation (49%–57% lower charge passed) compared to that of plain concrete with the same RCA content, but did not improve the 7-day flexural or 28-day compressive strengths. These limited mixtures and tests suggest that the modified gradation using natural aggregates improved concrete properties but modified gradations with RCA from non-pavement concrete sources can be problematic.

Concretes with 50% RCA had properties that were comparable to those of the control concretes when 20% of the cement was replaced with Class C fly ash. Mixtures in this study that used 30% RCA as coarse aggregate and no fly ash had fresh concrete properties and developed mechanical and durability properties that were similar to (or better than) the properties of control (no RCA) mixtures. Concrete paving mixtures that contain 100% RCA and fly ash can be produced that meet INDOT specifications for fresh and hardened concrete properties, but extra attention to aggregate moisture, water reducer dosages and w/cm may be necessary to achieve a mixture with appropriate workability.

The Benefit-Cost analysis (BCA) developed under this project, as discussed in Chapter 4, showed that using RCA can reduce aggregate costs, resulting in measureable project-wide savings. Cost savings, or lack of savings, related to using RCA can be readily identified using project-specific data, or general estimates.

With proper inputs this model can provide:

- An estimate of how much RCA can be expected from the removal of an existing pavement
- Cost comparisons between using different amounts of RCA versus natural aggregate for a particular project
- Cost comparisons between using the RCA in the concrete mixture and/or in the base structure

This easy-to-use tool can help engineers and other decision-makers to optimize resources and minimize aggregate related costs.

In conclusion, this study demonstrated that RCA crushed from existing INDOT pavements can replace up to 100% of the coarse aggregate and still meet INDOT's specification for concrete paving mixtures provided appropriate mixture design modifications (i.e., chemical and mineral admixtures, proper w/cm, etc.) are undertaken. However, considering the limited scope of this study (only one source of RCA, one Class C fly ash and two natural aggregate sources were used), plus the desire to maintain concrete mixture quality and durability levels at or above current levels, and the potential variability in the material properties of RCA, it is recommended that for standard practices, the amount of RCA coarse aggregate be more limited at this time. Durable concrete that contains RCA coarse aggregate made from INDOT's old concrete pavements in quantities up to 30% RCA with plain concrete, or 50% RCA with fly ash concrete, can be used successfully in new concrete pavement structures. This practice can lead to good resource management, quality concrete pavements and potential cost savings.

6. GENERAL RECOMMENDATIONS FOR USE OF RCA IN INDOT PAVEMENT CONCRETES

As the final outcome from this study, the following recommendations are proposed regarding the use of RCA in INDOT paving concretes:

- RCA should be required to meet existing INDOT requirements for #8 AP aggregates. In addition the following conditions are recommended:
    - The Brine Freeze and Thaw Soundness requirements should be used in place of the Sodium Sulfate Soundness for acceptance (similar to 904.03, Note 3).
    - RCA materials having absorption values between 5.0 and 6.0 percent that pass AP testing may be used if proper handling techniques are employed, including pre-wetting of RCA stockpiles (similar to 904.03, Note 4).
- RCA produced from existing INDOT concrete pavements is preferred, and those pavements should be evaluated prior to recycling to identify any existing materials related distresses that could impair the RCA's long-term durability. If the concrete pavement was placed prior to the establishment of INDOT AP quality aggregate standards and F/T durability is a concern, then cores taken at the joints and examined by a trained concrete petrographer can establish whether the aggregate has been F/T durable.
- RCA from variable and unknown sources should not be allowed unless they can be tested and shown consistently to have properties passing INDOT's AP standard and specifications for aggregates used in concrete pavements. Test should include ITM 210 F/T testing and ITM 209 Brine F/T Soundness testing but sulfate soundness testing need not be required.
- The approval process for the use of RCA in INDOT pavement concrete should include field trial batches to ensure the ability of achieving workable concrete with the desired w/cm and air content.
- The determination of moisture content of RCA at time of batching is critical for proper adjustments of the mix water. It should be noted that if the moisture content of the RCA is less than SSD condition, then slump may change quickly after initial batching as water is absorbed.
- A quality paving concrete that meets INDOT specifications can be produced using some amount of RCA as a replacement for AP coarse aggregate. Replacement levels of up to 30% RCA for plain concrete and up to 50% for concrete containing approximately 20% Class C fly ash can result in paving concrete with properties very similar to concrete without RCA while using common batching and construction practices for producing quality paving concrete. Good quality concretes containing 100% RCA can be produced but the use of mineral and chemical admixtures is recommended and extra attention to appropriate proportioning is needed.
- It is recommended that RCA be pre-wetted (i.e., aggregate piles should be kept moist, near SSD) and the aggregate moisture content determined with good accuracy in accordance with ASTM C 127 and/or AASHTO T 85.
- The use of fly ash is recommended in RCA concrete, especially at higher aggregate replacement levels since it has been proven that fly ash generally improves the mechanical and durability properties of most concrete mixtures, the same properties that are often somewhat reduced in RCA concrete.
- Using the pressure meter to determine the fresh air content in RCA mixtures is valid, but additional side-by-side measurements with the volumetric method are recommended until greater confidence is achieved with a variety of RCA mixtures and RCA sources.
- The water-soluble chloride content of RCA should be determined for each RCA source as RCA can contain water soluble chlorides at levels that are higher than many natural aggregates. Elevated chlorides in the mixture can interfere with set time, admixture behavior, certain test results and corrosion of steel in the concrete. If corrosion of steel is a potential concern as in reinforce concrete elements then recommendations for maximum total chloride content given in ACI 222 *Corrosion of Metals in Concrete* should be followed.
- Use caution in interpreting the results of electrical conductance/resistance test for estimating penetrability/permeability of concrete that contains RCA as RCA can contribute additional ions to the paste that may interfere with obtaining test results that accurately reflect penetrability/permeability.
- If the RCA is from more than one source than the range of specific gravity and absorption values of the RCA sources should be determined in accordance to AASHTO T 85, and the range of values obtained shall be reported. If variations in absorption or specific gravities preclude satisfactory production of PCC mixtures, independent stockpiles of materials will be sampled, tested, and approved prior to use (similar to INDOT 904.03, Note 4). It is recommended that the guidelines provided by AASHTO MP 16-10 *Provisional Standard for Reclaimed Concrete Aggregate for Use as coarse Aggregate in Hydraulic Cement* (Section 7.5) be followed, which states specific gravities shall not vary by more than 0.100, and absorption by more than 0.8% in a given stockpile.
- When a variety of options for using RCA are available, an economic analysis can be conducted to determine the optimal use of resources and realize maximum cost savings.
- Encourage the use of RCA as a viable alternative to natural coarse aggregate in concrete paving mixtures. The use and availability of RCA can keep aggregate costs competitive and result in measurable savings for new concrete pavement construction, especially in regions in which quality natural aggregates are less available.
- Continue to monitor the performance of the field trial placements along the shoulders of US 231 near the intersection of River Road (see Chapter 8).

7. RECOMMENDATIONS FOR FUTURE STUDY

This study examined several issues related to the use of RCA in paving concrete which has led to many answers and insights. Additional points that are considered to be important with respect to the use of RCA in concrete recommended for the future studies are listed below:

- The potential effects of RCA chloride content in accelerating corrosion, interfering with set time and behavior of certain admixtures should be evaluated as it is likely that RCA with elevated chloride contents will contribute additional chlorides to the pore solution of concrete.

- The effect of other cementitious materials beside Class C fly ash (e.g., slag cement, Class F fly ash and natural pozzolans) on the properties of RCA concrete also should be studied as they may have beneficial contributions in the development of the application of RCA concrete.
- The effect of using RCA from sources other than INDOT pavements on concrete properties should be evaluated as such data will be helpful with respect to effective utilization of recycled concrete and may lead to additional cost savings.
- Further study of modifying the aggregate gradation using natural aggregate to produce a more densely packed gradation could be lead to improved fresh and hardened concrete properties.
- Establishing a safe level at which RCA fines could be successfully included in a concrete mixture would further decrease the waste from a reconstruction project and potentially increase the cost savings realized using RCA.
- The relatively higher amount of potassium ions found in RCA's leachate compared to that of natural aggregates should be evaluated since higher alkali content in concrete may lead to the increase risk of alkali-silica reaction (ASR).

8. FIELD TRIAL PAVING OF US 231

Based on SPR 3309 project results, concrete containing RCA was placed in the shoulders of US 231 in two trial sections, one using 30% RCA and another with 50% RCA as the coarse aggregate. Details of the paving plan are shown in Figure 8.1 below.

Prior to placement, the mixture design was developed based on trial batching at the on-site batch plant. Fly ash was not available for paving and, because of historical concerns with low early strength gains with the cement being used, the cement content was kept higher than typical (see Figure B.3, Appendix B for the mill certificate for the cement used). The concrete shoulders were placed on May 14, 2012, using slip-form pavers and typical concrete paving techniques. Both INDOT and the contractor sampled and tested the fresh concrete mixture at the paving site using standard procedures.

The following summary is based on field observations and verbal communications at the time of placement.

Placement of the 30% RCA Concrete

Weather was sunny, light breeze mid-60s rising to mid-70s. Mixture design used included:

- 611# Essroc cement, Logansport
- No fly ash
- Typical WR dosages (WRDA 82)

- **8:20 am**: Paving outside shoulder of NB River Rd. with 100% gravel CA mix (611# cement).
- **10:00 am**: Began placing 30% RCA mixture at STA 654+00, outside shoulder of NB River Rd. Pavement stamped "1 30" to indicate sublot 1 with 30% RCA.

Three concrete loads brought paving up to the beginning of the curve at the intersection of NB South River Rd and US 231. Concrete samples tested by E & B Paving, Inc.:

- Air = 5.2%
- Slump = 1.5 in

Finishers commented that the RCA mixture closed well and finished nicely, better than the 100% gravel mixture. Edge looked very good, clean and sharp as shown in Figure 8.2.

- **10:20 am**: Pause in paving—adjusting air back at plant.
- **10:40 am**: Trucks 4 and 5 arrive and begin placing at the curve. Concrete tested by E & B:

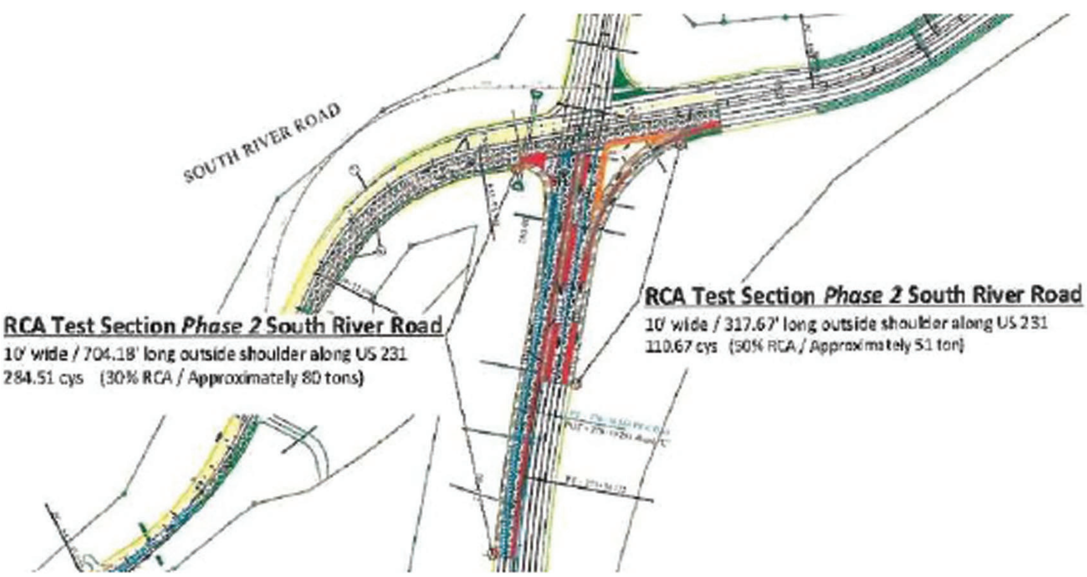


Figure 8.1 Paving section map of US 231.

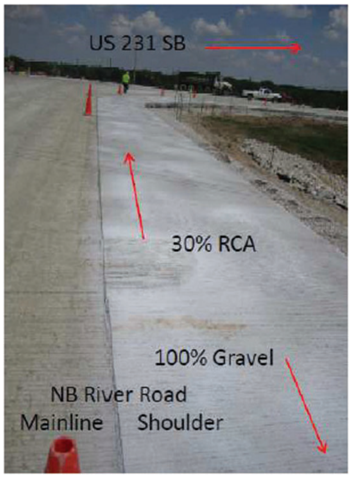


Figure 8.2 US 231 shoulder paved with 30% coarse RCA.

- Air = 5.6%
- Slump = 1.25 in

The mixture that sat for approximately 20 minutes was a bit dry and stiff by the time additional concrete arrived and was placed. There were some challenges in placing and finishing this mixture both because it was drier and was being placed on the curve where the pavement widens. Finishers worked with it until it was smooth. They used a small amount of water sprinkled on the surface as a finishing aid, when necessary.

- **11:00 am**: Heading SB along outside shoulder of US 231 past the curve. STA 280+00 is the first STA marking on US231 after curve/intersection. The trucks delivered concrete at regular intervals and slip form paver moved along at a steady pace. Continuous progress of paving was being made with no more than a 5 minute pause between trucks. Concrete surface continues to close easily and finishes well. Edge continues to stay sharp and clean.
- **11:10 am**: Concrete sampled and tested by E & B:
  - Slump = 2 in
  - Air = 7.1%
- **11:34 am**: Concrete sampled and tested by E & B and INDOT:
  - Slump = 2 in
  - Air = 6.8% (E & B)
  - Air = 6.3% (INDOT)
  - Beams made
- **1:00 pm**: Nearing the end of 30% RCA test section. STA 274+00 plus one panel was the end of the 30% RCA test section and was stamped R-30 (Figure 8.3).

Placement of Concrete Shoulder Containing 50% RCA

Weather continued to be sunny with temperatures in the mid-70s.

- **1:40 pm**: Paving the 50% RCA mixture begins at a header (2 panels N of STA 3+00) along outside shoulder of NB ramp from US 231 to River Rd. Paving moves southward. Concrete from truck #3 sampled and tested:
  - Slump = 2 in
  - Air = 5.9%
- **2:17 pm**: Construction operation is steady. Mixture finishes well, closes nicely and edge is sharp and clean.

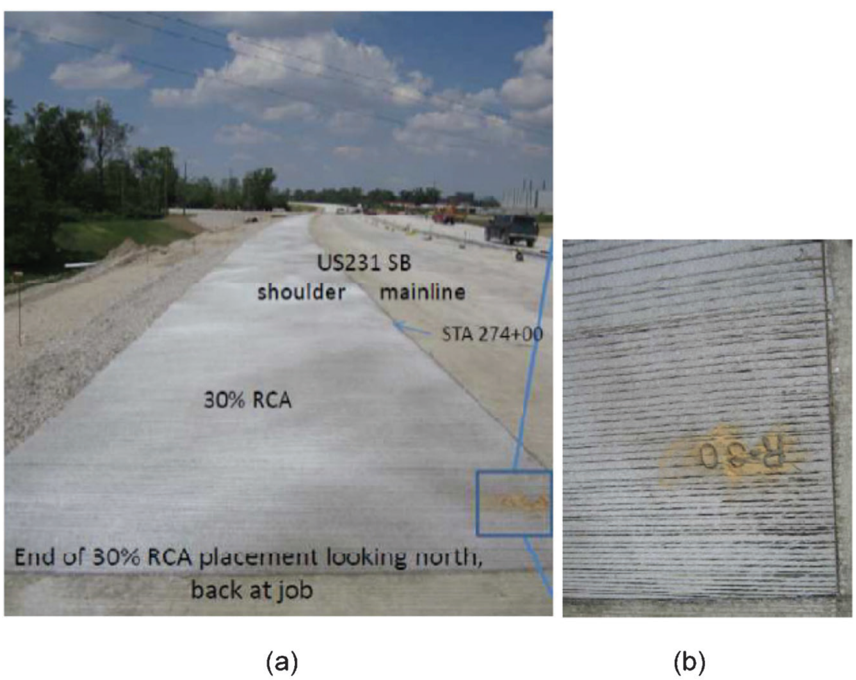


Figure 8.3 (a) US 231 shoulder paved with 30% coarse RCA (looking north), (b) finished surface of shoulder paved with 30% RCA stamped R-30.

(a) (b)

Figure 8.4 (a) Paving US 231 shoulder with concrete containing 50% coarse RCA, (b) Stamp on US 231 shoulder concrete containing 50% coarse RCA.

Surface tined and curing compound applied generally 30–45 min after concrete is placed.

- **2:30 pm**: Occasional 10–12 min lag between trucks.
- **2:40 pm**: Concrete sample tested at STA 279+20:
  - Slump = 2 in
  - Air = 6.7% (E & B)
  - Air = 6.3% (INDOT)
- **3:30–4:00 pm**: Paving 50% RCA ended at STA 277+50. R-50 is stamped into pavement (as seen in Figure 8.4). Paving the shoulder continues with 100% gravel CA.

REFERENCES

1. Rudy, A. Optimization of Mixture Proportions for Concrete Pavements—Influence of Supplementary Cementitious Materials, Paste Content and Aggregate Gradation. Ph.D. Thesis, Purdue University Graduate School, 2009, 382 pp.
2. American Concrete Pavement Association (ACPA). Recycling Concrete Pavement. *Engineering Bulletin*, ACPA, 2009, 84 pp.
3. Sturtevant, J. R., D. L. Gress, and M. B. Snyder. Performance of Rigid Pavement Containing Recycled Concrete Aggregates. *86th Annual Transportation Research Board Meeting (CD-ROM)*, Washington, D.C., Jan. 2007.
4. Liu, J., and B. Chen. Property of High Strength Concrete Made with Field Demolished Concrete Aggregates. *87th Annual Transportation Research Board Meeting (CD-ROM)*, Jan. 2008.
5. Smith, J. T., and S. L. Tighe. Recycled Concrete Aggregate—A Viable Aggregate Source for Concrete Pavements. *87th Annual Transportation Research Board Meeting (CD-ROM)*, Washington, D.C., Jan. 2008.
6. Roesler, J. R., and J. G. Hunley. *Performance of I-57 Recycled Concrete Pavement*. Research Report. Illinois Center for Transportation, 2008, 48 pp.
7. Kou, S. C., C. S. Poon, and D. Chan. Influence of Fly Ash as Cement Replacement on the Properties of Recycled Aggregate Concrete. *Journal of Materials in Civil Engineering*, Vol. 19, No. 9, 2007, pp. 709–717.
8. Gomez-Soberon, J. M. V. Porosity of Recycled Concrete with Substitution of Recycled Concrete Aggregate-and experimental study. *Cement and Concrete Research*, Vol. 32, 2002, pp. 1301–1311.
9. Poon, C. S., Z. H. Shui, L. Lam, H. Fok, and S. C. Kou. Influence of Moisture States of Natural and Recycled Aggregates on the Slump and Compressive Strength of Concrete. *Cement and Concrete Research*, Vol. 34, 2004, pp. 31–36.
10. Etxeberria, M., E. Vanquez, and M. Barra. Influence of Amount of Recycled Coarse Aggregates and Production Process on Properties of Recycled Aggregate Concrete. *Cement and Concrete Research*, Vol. 37, 2007, pp. 735–742.
11. Xiao, J., J. Li, and C. Zhang. Mechanical Properties of Recycled Aggregate Concrete under Uniaxial Loading. *Cement and Concrete Research*, Vol. 35, 2005, pp. 1187–1194.
12. Ann, K. Y., H. Y. Moon, Y. B. Kim, and J. Ryou. Durability of Recycled Aggregate Concrete Using Pozzolanic Materials. *Waste Management*, Vol. 28, 2008, pp. 993–999.
13. Tam, V. W. Y., and C. M. Tam. Assessment of Durability of Recycled Aggregate Concrete Produced by Two-Stage Mixing Approach. *Journal of Materials and Sciences*, Vol. 42, 2007, pp. 3592–3602.
14. Fathizal, G. New Mixture Proportioning Method for Concrete Made with Coarse Recycled Concrete Aggregate. *Journal of Materials in Civil Engineering*, 2009, pp. 601–611.
15. Verian, K. P. Using Recycled Concrete as Aggregate in Concrete Pavements. Master Thesis, Purdue University Graduate School, 2012, 192 pp.
16. Indiana Department of Transportation. *Specifications Standards*. Indiana Department of Transportation, Indianapolis, 2010.
17. John, D. A. S., A. B. Poole, and I. Sims. *Concrete Petrography: A Handbook of Investigative Techniques*. Wiley & Sons Inc., New York, 1998, 474 pp.
18. Shilstone, J. M. Concrete Mixture Optimization. *Concrete International*, American Concrete Institute, June 1990, pp. 33–39.

19. Haddock, J. E., T. D. White, and E. Rismantojo. *Aggregate Tests for Hot-Mix Asphalt Mixtures Used in Pavements*. NCHRP Report 557. Transportation Research Board, 2006. (http://www.nap.edu/catalog.php?record_id=13977)
20. Castro, J., D. Bentz, and J. Weiss. Effect of Sample Conditioning on the Water Absorption of Concrete. *Cement and Concrete Composites*, Vol. 33, No. 8, 2011, pp. 805–813.
21. NT Build 492. *Chloride Migration Coefficient from Non-Steady-State Migration Experiments*. Nordtest, 0283-7153, 1999.
22. Kuennen, T. The Economics of Recycling. *Rock Products*. October 1, 2007.
23. Abramowits, H., and Y. Sun. *Municipal Solid Waste Characterization Study for Indiana*. Purdue University, Calument, Indiana Department of Environmental Management and Recycling Market Development Board, 2012, (http://www.in.gov/idem/recycle/files/msw_characterizarion_study.pdf).
24. Mindess, S., and J. S. Young. *Concrete*. Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1981, pp. 117–118.
25. Snyder, M. B., J. M. Vandenbossche, K. D. Smith, and M. Wade. *Synthesis on Recycled Concrete Aggregate*. Interim Report-Task A, DTFH61-93-C00133. Federal Highway Administration (FHWA), Washington, D.C., 1994.
26. Epps, J. A., D. N. Little, R. J. Holmgren, and R. L. Terrel. *Guidelines for Recycling Pavement Materials*. NCHRP Report 224, Transportation Research Board, Washington, D.C., 1980.
27. Yrjanson, W. *Recycling of Portland Cement Concrete Pavements*. Synthesis of Highway Practice 154. National Cooperative Highway Research Program, Transportation Research Board, National Research Council Washington, D.C., December 1989.
28. Federal Highway Administration (FHWA). *Use of Recycled Concrete Pavement as Aggregate in Hydraulic-Cement Concrete Pavement*. Technical Advisory T 5040.37, U.S. Department of Transportation, Federal Highway Administration (FHWA), 2007.
29. Wade, M. J., G. D. Cuttel, J. M. Vandenbossche, H. T. Yu, K. D. Smith, and M. B. Snyder. *Performance of Concrete Pavements Containing Recycled Concrete Aggregate*. FHWA-RD-96-164. Federal Highway Administration. U.S. DOT. Washington, D.C., 1997.
30. Won, M. Use of Crushed Concrete as Coarse Aggregates in Concrete Pavement. *Proceedings of the International Workshop on Best Practices for Concrete Pavements*, held in Recife, Brazil. IBRACON. São Paolo, Brazil, 2007.
31. Gardner, K., and S. Greenwood. *Sustainable Highways Through The Use of Carbon Sequestering Construction Materials*. Project 35, University of New Hampshire. Durham New Hampshire. http://rmrc.wisc.edu/wp-content/uploads/2012/10/Proj35FinalRpt.pdf (last accessed 7/24/13).
32. Olorunsogo, F. T., and N. Padayachee. Performance of Recycled Aggregate Concrete Monitored by Durability Indexes. *Cement and Concrete Research*, Vol. 32, 2002, pp. 179–185.
33. Sturtevant, J. R., D. L. Gress, and M. B. Snyder. Performance of Rigid Pavement Containing Recycled Concrete Aggregates. *86th Annual Transportation Research Board Meeting (CD-ROM)*, Washington, D.C., Jan. 2007.
34. Abbas, A., G. Fathizal, O. B. Isgor, A. G. Razaqpur, B. Fournier, and S. Foo, S. Durability of Recycled Aggregate Concrete Designed with Equivalent Mortar Volume Method. *Cement and Concrete Composites*, Vol. 31, 2009, pp. 555–563.
35. NHI. *Techniques for Pavement Rehabilitation—Participant's Manual*. National Highway Institute, U.S.D.O.T. Washington, D.C., 1998.
36. American Concrete Institute (ACI). *Removal and Reuse of Hardened Concrete*. ACI 555R-01. American Concrete Institute. Farmington Hills, Michigan, 2001.
37. Katz, A. Properties of Concrete Made with Recycled Aggregate from Partially Hydrated Old Concrete. *Cement and Concrete Research*, Vol. 33, 2003, pp. 703–711.
38. Topcu, I. B., and S. Sengel. Properties of Concretes Produced with Waste Concrete Aggregate. *Cement and Concrete Research*, Vol. 34, 2004, pp. 1307–1312.
39. Angulo, S. C., P. M. Carrijo, A. D. Figueiredo, A. P. Chaves, and V. M. John. On the Classification of Mixed Construction and Demolition Waste Aggregate by Porosity and Its Impact on the Mechanical Performance of Concrete. *Materials and Structures*, Vol. 43, pp. 519–528, 2009. doi: 10.1617/s11527-009-9508-9
40. Gokce, A., S. Nagataki, T. Saeki, and M. Hisada. Freezing and thawing resistance of air-entrained concrete incorporating recycled coarse aggregate: the role of air content in demolished concrete. *Cement and Concrete Research*, Vol. 34, 2004, pp. 799–806.
41. Zaharieva, R., F. Buyle-Bodin, and E. Wirquin. Frost resistance of recycled aggregate concrete. *Cement and Concrete Research*, Vol. 34, 2004, pp. 1927–1932.
42. Salem, R. M., E. G. Burdette, and N. M. Jackson. Resistance to freezing and thawing of recycled aggregate concrete. *ACI Materials Journal*, Vol. 100, 2003, pp. 216–221.
43. Vancura, M., L. Khazanovich, and D. Tompkins. Reappraisal of Recycled Concrete Aggregate in Concretes for Rigid Pavements. In *Journal of the Transportation Research Board*, No. 2113, Transportation Research Board of the National Academies, Washington, D.C., 2009, pp. 149–155.
44. Yang, K. H., H. S. Chung, and A. F. Ashour. Influence of Type and Replacement Level of Recycled Aggregates on Concrete Properties. *ACI Materials Journal*, 2008, pp. 289–296.
45. Hansen, T. C. Recycled Aggregates and Recycled Aggregate Concrete Second State-of-the-Art Report Developments 1945–1985. *Materials and Structures*, Vol. 1, No. 111, Springer Netherlands, May-June, 1986, pp. 201–246.
46. Rahal, K. Mechanical Properties of Concrete with Recycled Coarse Aggregate. *Building and Environment*, Vol. 42, 2007, pp. 407–415.
47. Smith, J. T., Recycled Concrete Aggregate—A Viable Aggregate Source For Concrete Pavements. PhD Thesis, Thesis, University of Waterloo, 2009, 206 pp.
48. Sagoe-Crentsil, K. K., T. Brown, and A. H. Taylor. Performance of Concrete Made with Commercially Produced Coarse Recycled Concrete Aggregate. *Cement and Concrete Research*, Vol. 31, 2001, pp. 707–712.
49. Frondistou-Yannas, Y. A. Progress in Concrete Technology, *Progress in Concrete Technology*, CANMET, Energy Mines and Resources Canada. Ottawa, Canada, 1980, pp. 639–684.
50. Ravindrarajah, R. S., Y. H. Loo, and C. T. Tam. Recycled Concrete as Fine and Coarse Aggregate in Concrete. *Magazine of Concrete Research*, Vol. 39, No. 141, 1987, pp. 214–220.

51. Li, X., and D. L. Gress. Mitigating Alkali–Silica Reaction in Concrete Containing Recycled Concrete Aggregate. In *Journal of the Transportation Research Board*, No. 1979, Transportation Research Board of the National Academies, Washington, D.C., 2006, pp. 30–35.
52. Neville, A. M. *Properties of Concrete* (ed. 4). Longman Group, Harlow, London, UK, 1995, 844 pp.
53. Mukai, T., et al. Study on Reuse of Waste Concrete for Aggregate for Concrete. Presented at the Seminar on Energy and Resources Conservation in Concrete Technology. Japan-U.S. Cooperative Science Program. Washington, D.C., 1979.
54. Buck, A. D. *Recycled Concrete*. Highway Research Record 430. Highway Research Board. Washington, D.C., 1973, pp. 1–8.
55. Fergus, J. The Effect of Mix Design on the Design of Pavement Structures When Utilizing Recycled Portland Cement Concrete as Aggregate. Ph.D. Thesis. Department of Civil Engineering, Michigan State University, 1980.
56. Cuttel, G. D., M. B. Snyder, J. M. Vandenbossche, and M. J. Wade. Performance of Rigid Pavement Containing Recycled Concrete Aggregates. In *Journal of the Transportation Research Board*, No. 1574, Transportation Research Board of the National Academies, Washington, D.C., 1997, pp. 89–98.
57. Krenn, H., and H. Stinglhammer. New from Old—Recycling Concrete Pavements. *Proceedings of the 7th International Symposium on Concrete Roads*, Vienna, 3–5 October 1994, Papers Sessions 2/3, pp. 147–150.
58. Ghosh, P., A. Hammond, and P. J. Tikalsky. Prediction of Equivalent Steady-State Chloride Diffusion Coefficients. *ACI Material Journal*, American Concrete Institute, Vol. 108, 2011, pp. 88–94.
59. Snyder, K. A., C. Ferraris, N. S. Martys, and E. J. Garboczi. Using Impedance Spectroscopy to Assess the Viability of the Rapid Chloride Test for Determining Concrete Conductivity. *Journal of Research of the National Institute of Standards and Technology*, National Institute of Standards and Technology, Vol. 105, 2000, pp. 497–509.
60. Edvardsen, C., and M. T. Jepsen. Chloride Migration Coefficients from Non-Steady-State Migration Experiments at Environment-Friendly "Green" Concrete. http://www.gronbeton.dk/artikler/Chloride%20migration%20coefficients.PDF (Accessed January 12, 2012).
61. AASHTO T 277. *Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration*. American Association of State Highway and Transportation Officials, Washington, D.C., 2007.

APPENDIX A. LITERATURE REVIEW

CONTENTS

A.1. INTRODUCTION

A.1.1. Background

The construction sector grows as human needs grow requiring large quantities of material for building new, and repairing and modifying existing buildings, highways, bridges, housing, public facilities and other infrastructures. Many materials used in construction require large amounts of aggregate including concrete which is comprised of approximately 70% to 80% aggregate. The aggregate has considerable influence on several concrete properties including strength, shrinkage, creep, and durability (*24*).

Problems may develop if construction is restricted due to depletion of existing sources, reduced availability of new sources, restrictions on developing new sources and the increased cost in mining and transportation. Using recycled aggregate (RA) may help to address some of these problems (*2*). Interest in portland cement concrete (PCC) made with recycled concrete aggregate (RCA) has increased steadily since the mid-1970's with widespread use of recycled aggregate concrete (RAC) in pavements and many other construction application beginning in the 1980's (*5*). Based on Federal Highway Administration's data 41 states allow RAC to be used in pavement and other applications (as shown in Figure A.1.1). Primarily, RCA has been used as base and subbase materials, in concrete and asphalt paving layers, as rip-rap, as general fill and embankment (*2*). However, there are several examples in the literature of RCA as aggregate in concrete pavements (*25*).

A.1.2. A Brief History of the Use of RCA in Concrete Pavement

The use of crushed concrete as a source of aggregate for new concrete in pavement construction is not new. One of the earliest documented uses of recycled concrete in pavement construction in the U.S. took place in Illinois more than 60 years ago when two RCA concrete paving lanes were added to a portion of U.S. 66 (*25*). Many European countries utilized post-World War II building rubble in new concrete pavement construction at about the same time (*27*).

After those early recycling efforts, little work was done in the U.S. in the area of concrete recycling until the mid-1970s, when interest and activity surged during a period of "environmental awakening." By the mid-1990s, nearly 100 U.S. highway paving projects had been constructed using RCA in the concrete for

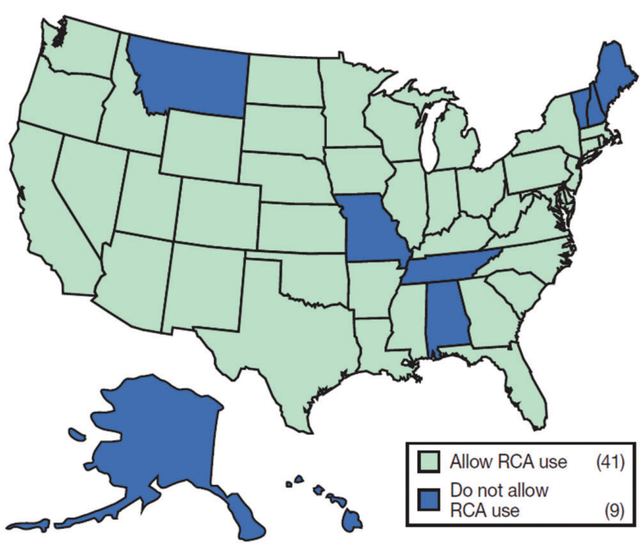


Figure A.1.1 States that allow the use of recycled concrete aggregate (RCA) in pavement and other applications (*2*).

pavements, including several that included RCA obtained from pavements exhibiting D-cracking and alkali-silica reaction (ASR) damage (*25*). A list of many of these projects is presented by Snyder et al. (*25*).

Most of these concrete pavements performed very well, but some performed so poorly as to be cautionary and, as a result, many states stopped using crushed concrete as aggregate in concrete for pavements. The following are examples of the problems that were observed on some RCA concrete pavements constructed in the 1970s and 1980s (and their apparent causes) (*29*):

- Deterioration and faulting of mid-panel cracks on jointed reinforced concrete pavements (JRCP) (indicating the need to design panel size and reinforcement in consideration of the potentially higher shrinkage and thermal coefficient of RCA concrete)
- Poor joint load transfer efficiency and development of excessive joint faulting on un-doweled pavements (due to lack of dowel bars and reduced aggregate interlock capability of crushed concrete particles, especially when the top size is reduced)
- Delayed development of recurrent D-cracking (associated with the use of crushed concrete containing aggregate that is highly susceptible to freeze-thaw damage in a structure that allows critical saturation to develop in freezing environment)

Other project reports from that era noted mixture workability problems (and suggested the use of natural sand and admixtures), and the observation of lower material strengths when RCA was substituted for natural aggregate without other mixture design modifications (*27*). These problems and findings illustrate the importance of considering the physical and mechanical properties of RCA in both the concrete mix design and the concrete pavement structural design.

Many field and laboratory investigations of RCA concrete have been performed in recent years, and much has been learned regarding its properties and characteristics. Highlights of these findings are presented in later sections of this review, and they have been used to improve concrete pavement design using RCA in Europe and Japan to the point where concrete recycling into concrete pavement structures is now standard practice in these parts of the world. For example, Austria recycles 100 percent of existing concrete pavement into the new pavement structure, using coarse RCA in the lower lift of two-lift concrete pavements while using the fines to stabilize the foundation layer.

In the U.S. today, nearly 100 percent of recovered concrete pavement is recycled, although generally it is not used in concrete pavement and is more often related to foundation layer, backfill and other applications (*2*). This probably is due to the ready availability of relatively inexpensive natural aggregate in many areas of the country, along with reluctance to accept the risk that is associated with lack of current experience in using RCA in concrete mixtures. A few states routinely are using (or allowing) the use of RCA in concrete paving mixtures. The most notable of these is Texas, which allows the practice and even reconstructed a major interstate highway using 100 percent recycled concrete (and no natural aggregate) in the late 1990s (*30*).

A.2. BENEFITS OF USING RECYCLED AGGREGATE

Using RCA instead of natural aggregate (NA) has a positive environmental impact. It can conserve on natural aggregate thereby reducing the need to open new mining areas and preserving the environment (*2*). In the past, construction waste usually ended up in the landfill. By crushing and reusing it as aggregates the amount of waste going into landfills is reduced (*2*).

The production and use of virgin aggregate consumes a great deal of energy (as motor fuel and/or electrical power) at each step of processing, including: the mining or extraction of the aggregate; the crushing, screening and washing; the stockpiling and/or transport to the job site; and the removal and disposal of material that is not recycled at the end of its period of use. Concrete recycling can greatly reduce the need for mining or extraction, and can reduce haul distances and fuel consumption associated with both supply and disposal (*2*).

Research by University of New Hampshire has shown that RCA has great value in reducing CO_2 which is a primary "greenhouse gas," through the mechanism known as sequestering carbon, or of spontaneous carbonation, in which atmospheric CO_2 reacts with calcium hydroxide ($Ca(OH)_2$), a by-product of the cement hydration in the concrete mortar to produce calcium carbonate. (i.e., the carbonation reaction is $Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$) (*31*).

Using RCA may reduce the construction costs. Some states estimated savings of up to 60% by using recycled aggregates as a replacement of natural aggregates (*2*). Using RCA has a good performance record in pavements. Several states have built concrete pavements using RCA and many of these pavements have shown good performance. One of the first U.S. applications of RCA in pavement construction occurred in the 1940's on U.S. Route 66 (*26*).

There are additional inducements for using RCA in new concrete. Recycling of concrete to produce RCA is a relatively simple process that involves breaking, removing and crushing hardened concrete from an acceptable source using standard aggregate-processing equipment (*2*). Because concrete aggregate has a higher value then aggregate used for base or fill RCA in new concrete is considered to have a higher life-cycle cost value then when used in other applications.

A.3. CHARACTERISTIC OF RECYCLED CONCRETE AGGREGATE

Recycled concrete aggregate (RCA) is produced by crushing and sorting existing concrete to be used as aggregates in new concrete. Some of the properties of RCA may differ from those of natural aggregates (NA). Since aggregate properties influence many of the plastic and hardened properties of concrete any differences in aggregate properties may result in different properties in concrete made from RCA compared to a similar mixture made from NA.

A.3.1. Mortar Content

During the production of RCA some of the old mortar falls away but much of the old original mortar inherently clings to the original aggregate and becomes part of the RCA product. This old mortar creates a more porous system in the RCA and is the primary factor for an increased absorption capacity and decreased specific gravity commonly associated with RCA compared to most NA (*2*). This higher absorption can lead to higher plastic shrinkage on RAC (*12, 32*). A higher mortar content in recycled aggregate also may contribute to a reduction in strength (*2*) and higher cracking rate in RAC pavement (*33*). The presence of old mortar attached to RCA creates greater areas of aggregate-paste interfaces in RAC which is also known as the interfacial transition zone (ITZ). ITZ is known as weak area in concrete where potential failure might occur. RAC has more ITZ than normal concrete because the ITZ in RAC includes the bonds between aggregate-old mortar, aggregate-new mortar, and old mortar-new mortar (*25*).

A.3.2. Specific Gravity

Many researchers report lower specific gravity for recycled aggregate than that of natural aggregate (as shown in Table A.3.1). As stated above, it is the presence of old mortar attached to the RCA that can lead to a lower specific gravity than what is common for natural aggregate typically used in concrete pavements (*2*).

TABLE A.3.1
Specific gravity of recycled aggregate and natural aggregate reported by different researchers

Author	Specific gravity (coarse aggregate) Recycled aggregate	Specific gravity (coarse aggregate) Natural aggregate
ACPA 2009 (*2*)	2.1–2.4	2.4–2.9
Gomez-Soberon 2002 (*8*) (surface dry)	2.35–2.42	2.59–67
Gomez-Soberon 2002 (*8*) (dry)	2.17–2.28	2.57–2.64
Poon et al. 2004 (*9*)	2.33–2.37	2.62
Ann et al. 2008 (*12*)	2.48	2.63
Xiao et al. 2005 (*11*)	2.52	2.82
Abbas et al. 2009 (SSD) (*34*)	2.42–2.5	2.71–2.74
Kou et al. 2007 (*7*)	2.49–2.57	2.62
Olorunsogo et al. 2002 (*32*)	2.6	2.61

A.3.3. Absorption

Most of studies have shown that RCA generally has higher absorptions than NA typically used in concrete pavements due to the somewhat porous old mortar attached (*12,32*). Some of these reported values are shown in Table A.3.2.

A.3.4. Influence of Crushing Process and Other Factors on RCA Properties

Most concrete recycling plants have both primary and secondary crushers. The primary crusher typically reduces the material size down to about 3-4 in [8–10 cm], while the secondary crusher further breaks the material to the desired maximum coarse aggregate size.

The three main types of crushers used in concrete recycling feature "jaw," "cone" and "impact" designs, which differ in how they crush the concrete. Different crushing processes remove different amounts of mortar from the original aggregate particles, and they produce different RCA product particle size distributions. Figure A.3.1 presents data from an FHWA-sponsored study that shows the particle size distributions produced when samples of the same concrete were crushed using three different processes. The degree of mortar removal and resulting particle size distribution also vary with the properties of the natural aggregate in the concrete that is being crushed.

Since mortar removal and particle size distribution vary with crushing process and source concrete properties, key properties of the RCA product also vary with these same parameters. In general, as particle size decreases, larger portions of the particles tend to comprise reclaimed mortar; as a result of the increased mortar content, particle absorption will increase and relative density (specific gravity) will decrease. This is illustrated in Table A.3.3.

TABLE A.3.2
Absorption of recycled aggregate (RA) and natural aggregate (NA) reported by different researchers

Author	Absorption (%) Recycled aggregate (RA)	Absorption (%) Natural aggregate (NA)
ACPA 2009 (*2*)	3.7–8.7	0.8–3.7
Gomez-Soberon 2002 (*8*)	5.83–8.16	0.88–1.49
Poon et al. 2004 (*9*)	6.28–7.56	1.24–1.25
Ann et al. 2008 (*12*)	4.25	0.73
Xiao et al. 2005 (*11*)	9.25	0.4
Abbas et al. 2009 (SSD) (*34*)	3.3–5.4	0.54–0.89
Kou et al. 2007 (*7*)	3.52–4.26	1.11–1.12

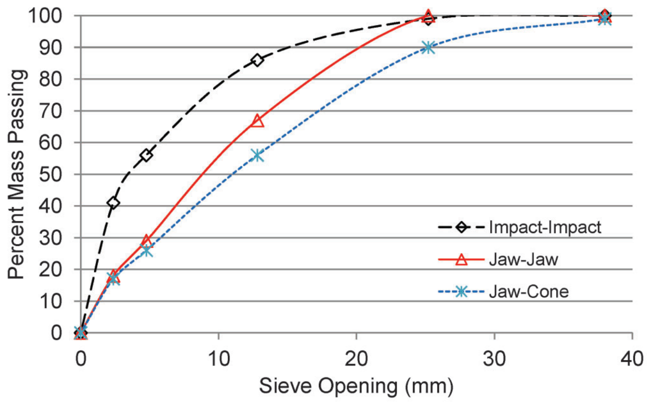


Figure A.3.1 Variation in particle size distribution for a single concrete source crushed in three different plants.

Since coarse RCA is most highly valued for use in concrete mixtures, it is often desirable to produce as much of this size fraction as possible. The yield of coarse aggregate from the recycling operation depends on many factors, including the type and quantity of natural coarse aggregate used in the source concrete, the quality and hardness of the concrete mortar, the breaking and removal operations and the crushing processes used. Loss of material through removal operations can be as high as 10 percent (for recycling of jointed reinforced concrete pavement with field removal of the wire mesh) and may approach zero for jointed plain concrete pavements. Crushing for larger top-size aggregate generally produces higher coarse aggregate yields because less crushing is necessary. For example, 55 to 60 percent coarse aggregate yield is common when crushing to ¾ in. [19 mm] top size, while 80 percent yield is not uncommon when crushing to 1.5 in. [28 mm] top size (*35*). Table A.3.4 summarizes reclamation efficiencies observed in an FHWA-sponsored study of various source concrete materials and crushing processes.

A.4. CHARACTERISITCS OF CONCRETE MADE WITH RCA

Aggregate characteristics affect the properties of the plastic and hardened concrete in which it is used. Therefore, if there are differences in aggregate properties of RCA compared to a NA this could lead to differences between the concrete containing RCA compared to concrete made with NA (*36*). This section explores these potential differences in concrete made with RCA in both the plastic and hardened state, and how other researchers may have managed these differences.

A.4.1. Fresh Concrete Properties

A.4.1.1. Workability

Workability of concrete is affected by several factors including but not limited to water content, aggregate type, aggregate size, shape and gradation, mixture proportion and temperature at mixing (*6*). The workability of concrete is often estimated using the slump test in accordance to ASTM C 143. Generally, a high slump suggests the concrete is more workable and a lower slump is a stiffer mix. Some researchers have reported that RAC may have less slump than normal concrete at the same w/c ratio (*5,6*). The decrease in workability of RAC may be attributed to the angularity of RCA, rough surface texture, and/or higher absorption capacity of recycled aggregate (*6*). To achieve similar workability as a mixture using natural aggregate (NA), the concrete made with coarse RCA may need 5% more water than normal concrete (NC) while concrete with both coarse and fine RCA may need approximately 15% more water (*6*). Results of workability from several researches are shown in Table A.4.1.

The use of admixtures may be the solution to achieving similar workability between RAC and normal concrete when the same w/c ratio is required (*5*).

TABLE A.3.3
Effects of particle size on RCA properties (*2*)

Sieve size	Percent retained	Bulk specific gravity	Percent absorption
1.0 in. (25 mm)	2	2.52	2.54
¾ in. (19 mm)	22	2.36	3.98
½ in. (12.5 mm)	33	2.34	4.50
⅜ in. (9.5 mm)	18	2.29	5.34
No. 4 (4.75 mm)	25	2.23	6.50
Weighted average	**100**	**2.31**	**5.00**

TABLE A.3.4
Effects of source concrete aggregate type and crushing process on coarse aggregate reclamation efficiency (percent)

	Source concrete aggregate type		
Crushing process	Limestone	Gravel	Granite
Jaw-Jaw-Roller	71	73	87
Jaw-Cone	73	80	76
Impact-Impact	44	63	53

A.4.1.2. Air Content

The air content of fresh concrete containing RCA is usually up to 0.6% higher than that of normal fresh concrete (*2*). The higher air content generally is assumed to be caused by the air that is entrained and entrapped in the reclaimed concrete mortar attached to the RCA (*29*).

Because RCA tends to be more porous, the air content measurement by the volumetric method (ASTM C 173) is recommended. However, the pressure method (ASTM C 231) can be used to measure the air content if a correction factor is used as when used on lightweight aggregate (*33*). Katz 2003 (*37*) used the gravimetric method (ASTM C 138) in measuring the air content of RAC and the result showed 4-5.5% higher air content on RAC.

A.4.2. Hardened Concrete Properties

A.4.2.1. Compressive Strength

Most studies have reported a decrease in compressive strength when using of RCA in concrete (*6–11,37*). The decreasing trend of compressive strength and tensile strength in concrete with increased RCA content may be explained by the presence of two kinds of interfacial transition zones (ITZ) in concrete made with

TABLE A.4.1
Reported workability of RAC compared to normal concrete

Author	Workability
Smith and Tighe 2008 (*5*)	Lower
ACPA 2009 (*2*), after FHWA 2007 (*28*), ACI 2001 (*36*)	Similar to slightly lower
Sturtevant et al. 2007 (*33*)	Lower
Liu and Chen 2008 (*4*)	Lower
Topcu et al. 2004 (*38*)	Lower

RCA. The ITZ represents the bond between aggregate and paste and is often weaker than either the aggregate or hydrated cement paste (*2*). In normal concrete, the ITZ occurs between aggregate and mortar while in concrete with RCA, the ITZ occurs between the original aggregate and old mortar and the reclaimed mortar and new mortar. The higher the percentage of RCA replacement there is in the concrete then theoretically the greater the potential reduction is in strength, as shown in Figure A.4.1. Table A.4.2. shows that concrete made with 100% recycled coarse aggregates has up to 25% lower compression strength than conventional concrete at 28 days (assuming the same w/c and cement quantity), although a few authors reported very little change or an increase in strength. Angulo et al. (*39*) related the reduction of compressive strength to an increase in porosity of recycled aggregates produced from a mix of concrete and masonry.

A.4.2.2 Flexural and Tensile Strength

A study by Katz (*37*) showed that flexural strength of RAC that contained 100% recycled coarse aggregate decreased approximately 10% compared to similar NC. Poon et al. (*9*) concluded that the decrease of flexural strength in RAC was noticeable especially when the concrete was made from saturated recycled aggregate.

The study by Katz (*37*) also showed that tensile strength of RAC has decreased around 6% than its reference. Other studies showed that reduction of tensile strength on RAC is up to 10% when the RCA replaces the coarse aggregate only however, when the aggregate replacement includes both coarse and fine RCA the tensile strength reduction increased to 10%–20% (*2*). Contrary to this, another study by Etxeberria et al. (*10*) showed higher tensile strength for RAC than normal concrete. The correlation between tensile strength and percentage replacement of RCA results from several studies by are shown in graph in Figure A.4.2.

A.4.2.3. Modulus of Elasticity

The term modulus of elasticity used herein refers to the static modulus of elasticity and is affected by the presence of reclaimed mortar in RAC. As shown in Figure A.4.3., most studies have shown that RAC had a lower modulus of elasticity than normal concrete (0% RCA), and the modulus of elasticity decreased as the percentage recycled aggregate increased (*7,10,11,25*). A study by Snyder et al. (*25*) showed that the modulus of elasticity of RAC range from 20-40% lower than that of normal concrete. ACPA (*2*) also noted that modulus elasticity of RAC with coarse aggregate replacement was 10-33% less than the modulus of elasticity of normal concrete (*36*). Angulo et al. (*39*) related the reduction of modulus to an increase in porosity of recycled aggregates produced from a mix of concrete and masonry.

A.4.2.4 Coefficient of Thermal Expansion (CTE)

Sturtevant et al. (*33*) noted that the coefficient of thermal expansion (CTE) was generally higher for pavement with recycled concrete than the control pavement. High CTE may increase the potential for mid-slab cracking and increase the rate of crack deterioration due to higher stresses and/or greater crack widths. Cores retrieved and tested from several test sites from around U.S. indicated that the CTE is approximately 10% higher on RAC compared with that of normal concrete, with a range of values up to approximately 30% higher (*29*).

A.4.2.5. Freezing-thawing Resistance

Smith et al. (*5*) showed that there was no significant difference in freeze-thaw resistance between RAC and normal concrete. Another study by Gokce et al. (*40*) resulted in poor resistance of RAC with coarse aggregate derived from non-air-entrained concrete. RAC made with recycled coarse aggregates that originated from air-entrained concretes was highly frost resistant and showed freeze-thaw resistance that was superior to that of normal concrete after subjected in 500 freezing and thawing cycles (*40*). However, Zaharieva et al. (*41*) showed that RAC had lower resistance to freezing and thawing than normal concrete due to the higher porosity and poorer mechanical characteristics of RAC (*42*).

A.4.2.6. Drying Shrinkage

The extent to which drying shrinkage occurs is a function of paste content and w/c ratio. Since RAC generally contains a higher paste content due to its reclaimed and new mortar, RAC tends to have the potential for higher drying shrinkage. Studies have found 20% to 50% higher shrinkage in concrete containing coarse RA and natural sand, and 70% to 100% higher shrinkage in concrete containing both coarse and fine RA compared to NC (*36*). Tam et al. (*13*) reported that shrinkage increased along with the increased percentage of recycled coarse aggregate in the concrete with nearly 100% increased shrinkage in RAC that contained 100% coarse RCA. Other studies reported similar trends in RAC that generally had higher drying shrinkage than normal concrete (*3,4,5,37*). Incorporating both recycled coarse aggregate and recycled fine aggregate showed the highest shrinkage in all ages of specimens (*4*). Vancura et al. (*43*) noted

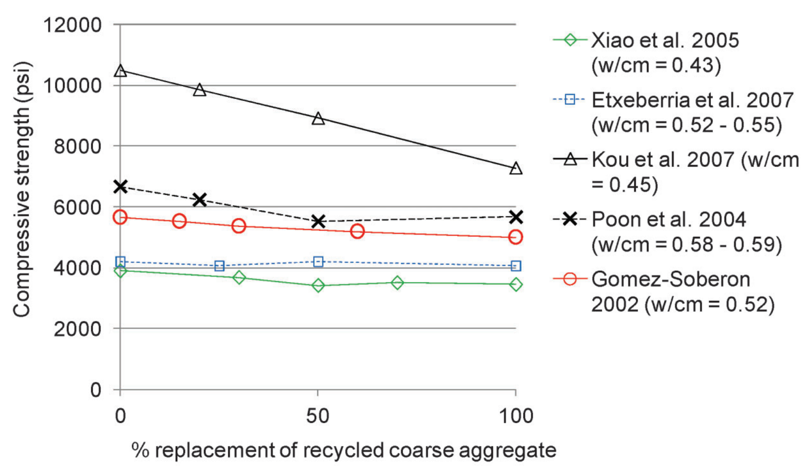


Figure A.4.1 Compressive strength variability with respect to percent replacement of recycled aggregate in RAC reported by several researchers.

TABLE A.4.2
Compressive strength of RAC compared to normal concrete reported by different researchers

Author	Compressive strength	% Replacement of recycled coarse aggregate
Etxeberria et al. 2007 (*10*)	20-25% lower	100
Roesler et al. 2009 (*6*)	2-10% lower	100
Xiao et al. 2005 (*11*)	~11% lower	100
Tam et al. 2007 (*13*)	~10% lower	100
ACPA 2009 (*2*) after FHWA 2007 (*28*), ACI 2001 (*36*), Hansen 1986 (*45*)	0-24% lower	—
Katz 2003 (*37*)	~25% lower	100
Rahal 2007 (*46*)	~10% lower	—
Smith 2009 (*47*)	Increase	15; 30 and 50
Sagoe-Crentsil et al. 2001 (*48*) after Frondistou-Yannas et al. 1980 (*49*), Ravindrarajah et al. 1987 (*50*)	10% lower	—
Sturtevant et al. 2007 (*33*)	Increase, except Minnesota 4 project	—

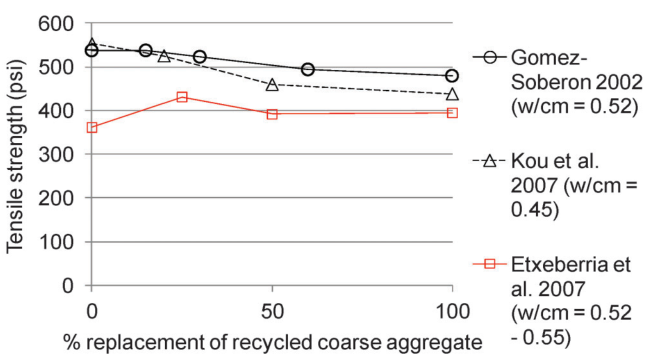


Figure A.4.2 Variation of tensile strength respect to percent replacement of recycled aggregate in RAC reported by several researchers.

that in a study by Yang et al. (*44*) the amount of reclaimed mortar attached to the RCA greatly affected the shrinkage of RAC.

A.4.2.7. Creep

The percentage replacement of recycled aggregate affects the creep of the RAC. Creep on RAC generally increased with increased amounts of recycled aggregate in RAC (*13*). ACPA (*2*) reported the creep of RAC typically 30 to 60 percent higher than that of normal concrete and it was due to the higher proportion of paste content in RAC.

A.4.2.8. Permeability

Size and continuity of the pores at any point during the hydration process in hydrated cement paste would control the coefficient of permeability. Permeability in RAC increased with the increase in the proportion of RCA. The increase of permeability generally leads to the decrease of chloride ion penetration resistance. Kou et al. (*7*) reported that RAC with 100% replacement of coarse RCA resulted in more than 40% decrease in chloride ion penetration resistance (test has been conducted based on ASTM C 1202 Rapid Chloride Permeability Test).

A.4.2.9. Density

The density of RAC tends to be less than NC due to its attached mortar which is more porous and creates a less dense matrix in the concrete (*2*). Several studies (*8,10,11*) showed that generally the increase of RA content in RAC contributes to the decrease of density of RAC (Figure A.4.4).

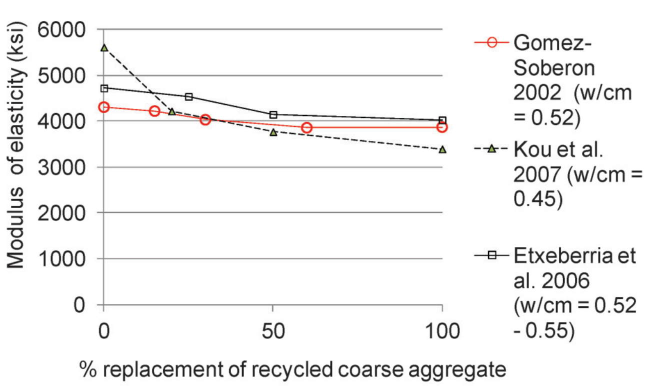


Figure A.4.3 Variation of modulus of elasticity with respect to percent replacement of recycled aggregate in RAC reported by several researchers.

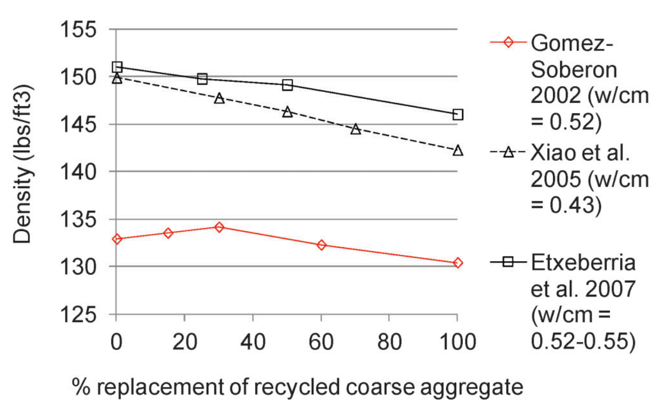


Figure A.4.4 Variation of density of concrete respect to percent replacement of recycled aggregate in RAC reported by several researchers.

A.5. CHALLENGES AND SUCCESS IN USING RCA

As discussed in the previous chapters the properties of RCA may differ from NA and so may the concrete made with each of these aggregate types. Generally RAC may have a tendency for lower strength (compressive, flexural, and tensile strength); higher shrinkage, creep, CTE and permeability; lower modulus of elasticity and density. Generally these differences lead to quality concerns of RAC compared with NC using the same mix design. Only two papers (out of 10) reported the use of fine RCA in their research project. Why recycled fine aggregate is rarely used and the challenge its use presents is discussed in Section A.5.4.

A.5.1. RCA Derived from D-cracked and ASR-damaged Concrete Pavements

RAC made from D-cracked pavement showed no significant difference in terms of freeze-thaw resistance when the aggregate size is limited to 19 mm since it larger aggregate particles susceptible to D-cracking expand the more during freeze-thaw cycles (*2*). Other methods used to reduce the freeze-thaw effect in RAC included reducing the paste permeability by using fly ash as supplementary cementitious material (SCM) or reducing w/c ratio, and/or reduce the exposure to water and saturation by using joint seals and pavement drainage system in RAC pavement (*2*).

ASR occurs when aggregates containing reactive silicates react with alkalis and hydroxyl ions in the cement to form a highly expansive gel. The expansive forces often cause the aggregate and the surrounding mortar to crack and deteriorate (*2*). The reclaimed mortar in RCA is inherently non-reactive, so the concentration of reactive silicates in RCA is generally reduced from the original concrete. Therefore concrete with processed RCA from an ASR-damaged concrete may tend to be less susceptible to ASR than those containing conventional silicate aggregates (*2*). Other researchers suggest that ASR related to RCA could be activated or reactivated if the original aggregate was potentially reactive and the alkali loading was high enough in the new concrete (*51*). RAC from ASR-damaged concrete has shown little evidence of recurrent ASR damage if precautionary measures are taken such using a low-alkali cement, Class F fly ash, slag cement and/or low w/c ratio (*2*).

A.5.2. Percentage Replacement of Recycled Aggregate in RAC

The percentage replacement of recycled aggregate varied among researchers and as did the inclusion of RCA fine aggregates, therefore there are difficulties in comparing reported results. From the literature, the percentages of coarse and fine RCA replacement used in ten studies from different authors are detailed in Table A.5.1.

As Table A.5.1 shows 9 out of 10 projects went up to 100% replacement of recycled coarse aggregate, and 8 out of 10 contained one or more replacement levels between 0% and 100% replacement with 6 out of 10 papers that contained a 50% replacement mix. Certain levels of replacement in RCA have been reported for its comparable quality in many properties with control concrete (0% RCA). A 20% coarse RCA replacement had no significant effect in concrete properties (*13*) while other studies showed that there is no significant impact in compressive strength and freezing- thawing resistance up to 30% level of coarse aggregate replacement (*5*).

A.5.3. Potential Ways to Improve the Performance of RAC

A.5.3.1. Using Fly Ash

It is commonly known that the RCA are more porous and contributes to a more permeable concrete (*2*). Permeability plays an important role in the durability of the concrete (*32*). The more permeable the concrete, the easier it is for water and/or other liquids that contain chemical substances to be penetrated which may make it less durable and contribute to damage in the concrete. The use of pozzolanic materials reduces the permeability which generally leads to more durable concrete. Fly ash (FA) and silica fume are widely used pozzolanic materials in concrete. Fly ash is more likely used in pavement than silica fume because it is less expensive and has fewer related workability and curing concerns.

The positive effects of using fly ash:

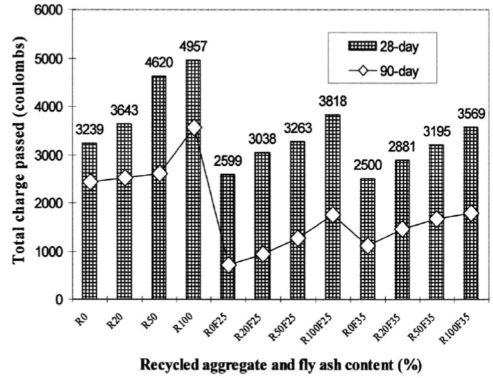
- FA increases the workability of concrete (*52*).
- FA reduces the permeability of concrete. FA increases the production of C-S-H in the concrete system which makes the concrete denser. The less permeability the concrete, the better resistance to chloride ion penetration (*7*).
- A recent study by Rudy (*1*) concluded that optimum fly ash concrete paving mixture should contain 22% of fly ash (by weight of total cementitious material) and current INDOT specifications allow up to 24% replacement (by total weight of cementitious material).

There are properties of fly ash that may need to be considered. Fly ash may delay the setting time of concrete. Unlike cement which reacts quickly with water, fly ash needs time before it reacts since it reacts with the product of water-cement reaction (CH) and water to produce C-S-H (*52*).

From Figure A.5.1, we can see that the higher percentage replacement of RCA the higher the amount of ions passed thru the concrete. It indicates the higher porosity of concrete with higher replacement of RCA. The porosity of the concrete became less over time due to the more complete hydration process but the relative difference in porosity between mixes remained the same.

TABLE A.5.1
Percentage replacement of RCA in the concrete mix design in different studies

No.	Author	Percentage replacement (by weight): Recycled coarse aggregate (RCA)	Percentage replacement (by weight): Recycled fine aggregate (RFA)
1	Smith et al. 2008 (*5*)	0%, 15%, 30%, 50%	0%
2	Xiao et al. 2005 (*11*)	0%, 30%, 50%, 70%, 100%	0%
3	Tam et al. 2007 (*13*)	0%, 20%, 100%	0%
4	Kou et al. 2007 (*7*)	0%, 20%, 50%, 100%	0%
5	Olorunsogo et al. 2007 (*32*)	0%, 50%, 100%	0%
6	Poon et al, 2004 (*9*)	0%, 20%, 50%, 100%	0%
7	Etxeberria et al. 2007 (*10*)	0%, 25%, 50%, 100%	0%
8	Sturtevant et al. 2007 (*33*)	0%, 100%	0%, 20%, 22%, 25%
9	Liu and Chen 2008 (*4*)	0%, 100%	0%, 100%
10	Gomez-Soberon 2002 (*8*)	0%, 15%, 30%, 60%, 100%	0%



R0: 0% RCA, 100% NA	R20: 20% RCA, 80% NA
R50: 50% RCA, 50% NA	R100: 100% RCA, 0% NA
R0F25: 0% RCA, 100% NA, 25% fly ash	R20F25: 20% RCA, 80% NA, 25% fly ash
R50F25: 50% RCA, 50% NA, 25% fly ash	R20: 20% RCA, 80% NA
R50: 50% RCA, 50% NA	R100: 100% RCA, 0% NA
R0F25: 0% RCA, 100% NA, 25% fly ash	R20F25: 20% RCA, 80% NA, 25% fly ash
R50F25: 50% RCA, 50% NA, 25% fly ash	R100F25: 100% RCA, 0% NA, 25% fly ash
R0F35: 0% RCA, 100% NA, 35% fly ash	R20F35: 20% RCA, 80% NA, 35% fly ash
R50F35: 50% RCA, 50% NA, 35% fly ash	R100F35: 100% RCA, 0% NA, 35% fly ash

Figure A.5.1 Chloride ion penetration in concrete made with various amounts of RCA and fly ash replacements (*7*).

A.5.3.2. Two-Stage Mixing Approach (TSMA)

A two-stage mixing approach (TSMA) has been developed by Tam et al. (*13*) to improve concrete quality using RCA, as shown in Figure A.5.2. During the first stage of mixing a layer of cement slurry forms on the surface of recycled aggregate that fills the cracks and voids and eventually creates a better ITZ. Improved strength by TSMA has been proven by Tam et al. (*13*) while the durability performance remains to be studied (*13*). The drawback to this procedure is the mixing time needed which is longer than normal mixing times (270 seconds Vs. 120 seconds).

A.5.3.3. Reducing the Mortar Content on RCA

Reducing the mortar content attached to the original aggregates in RCA has been shown to improve the quality of the final product (*2*). Reducing mortar content can be done by reducing the RCA to a smaller size than its original aggregate size during the production (e.g., waste concrete with a maximum aggregate size of 1 in is crushed into RCA with maximum aggregate size ¾ in). As discussed in Section A.3.4 crushing and processing techniques also can influence the mortar content.

A.5.3.4 Adjustment to Mix Design Proportions

Some studies have shown that an adjustment to the mix design proportions also can compensate for the change in properties when using RCA in concrete. To offset the reduction in strength in concrete with RA, cement can be added. For example, concrete with 50% RCA replacement needs approximately 6% more cement than its control concrete to achieve comparable compressive strength while concrete with 100% RCA may need 8.3% more cement (*10*). Also Etxeberria et al. (*10*) has shown that different proportions of cement, aggregate and superplasticizer may be needed for RAC compared to normal concrete in order to achieve comparable strengths. Table A.5.2. and Table A.5.3. show the mix design and the concrete properties respectively examined by Etxeberria et al. (*10*).

The basic proportioning of RAC can be accomplished using the same procedures for proportioning normal concrete. The

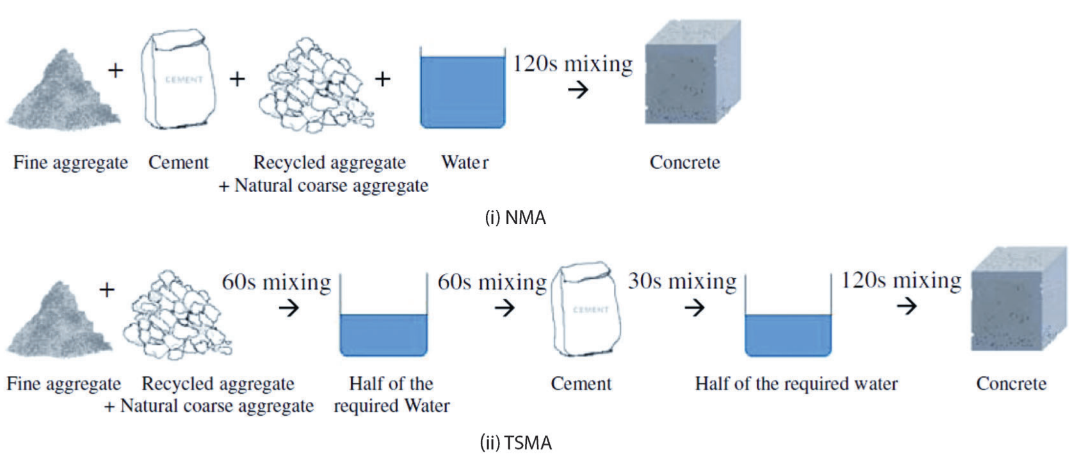


Figure A.5.2 Mixing procedures of the (i) normal mixing approach and (ii) two-stage mixing approach (*13*).

TABLE A.5.2
Definitive dosage for control concretes (CC), 25% recycled aggregate concrete (RC25), 50% recycled aggregate concrete (RC50) and 100% recycled aggregate concrete (RC100) (*10*)

	S	A1	RA1	A2	RA2	A3	RA3	Cement	Additive %	W	Effective w/c
CC	765.1	332.7		295.1		579.2		300	0.97	165	0.55
RC25	765.1	249.5	72.8	221.3	64.6	434.4	128.3	300	0.79	165	0.55
RC50	739	172.1	150.6	147.4	129.2	289.4	256.6	318	0.84	165	0.52
RC100	683.2		425.8		306.4		391.2	325	1.38	162	0.5

CC: control concrete. RC25, RC50 and RC100: concrete with 25%, 50% and 100% recycled coarse aggregates respectively.

S sand: A1, A2 and A3: natural coarse aggregate 4/10 mm, 10/16 mm and 16/25 mm, respectively. RA1, RA2 and RA3: Recycled coarse aggregate 4/10 mm, 10/16 mm and 16/25 mm, respectively. W: water.

Aggregates, cement and water are given in mass (kg) for 1 m^3 of concrete.

TABLE A.5.3
Mechanical properties of cubic test elements at 28 days of curing (*10*)

	Density (kg/dm^3)	Compressive strength (MPa)	Tensile strength (MPa)	Modulus of elasticity (MPa)
CC	2.42	29	2.49	32,561.7
RC25	2.40	28	2.97	31,300.4
RC50	2.39	29	2.70	28,591.7
RC100	2.34	28	2.72	27,764.0

procedure of proportioning the mix design of RAC generally can be adopted from ACI 555R-01 (*2*), with the following exceptions:

- The lower specific gravity of RCA should be considered in determining the aggregate batch weights on the basis of absolute volumes of components.
- In order to achieve the same slump as for normal concrete, the free water content of a mixture containing coarse RCA should be increased about 5 percent. Additional water can be reduced or even be eliminated through optimized gradations, or the use of chemical and/or mineral admixtures (e.g., fly ash, water reducers, superplasticizer).
- The ratio of fine aggregate to coarse aggregate should be approximately the same as for the control concrete.

A.5.3.5. Additional Mix Design Modifications

Well-rounded, compact aggregate particles with a smooth surface texture are most effective in promoting concrete workability, but RCA particles tend to be angular and rough-textured, which can increase the harshness of fresh concrete mixtures—especially when recycled concrete *fine aggregate* replaces conventional sands.

To produce the same workability as a conventional concrete mixture, up to 5 percent more water may be required for mixtures containing only coarse RCA ((*2*) after (*53*)) and up to 15 percent more water is needed for mixtures containing both coarse and fine RCA ((*2*) after (*54*)). The use of additional water while holding other mix design parameters approximately constant increases the water-cementitious materials ratio, resulting in corresponding decreases in strength. For this reason, it is most common to limit the use of fine RCA to less than 30 percent of total fine aggregate, and/or to use chemical admixtures (water reducers and superplasticizers) and/or fly ash to offset any lost workability (*2*).

As noted previously, RCA concrete strength generally varies directly with the strength of the source concrete and varies inversely with the reclaimed mortar content (both coarse and fine RCA) and water-to-cement ratio for the new concrete mixture (*2*). Strength reductions due to the use of RCA in concrete mixtures can be offset (or eliminated) by modifying the concrete mixture design to reduce the water-cementitious materials ratio (often in combination with the use of water-reducing admixtures) and/or the use of mineral admixtures such as fly ash or slag cement. Blends of natural and recycled fines (up to about 30 percent replacement) have also been associated with higher strengths than can be obtained from using either natural or recycled materials alone. This increase in strength has been attributed to improvements in the gradation of the blended fine aggregate, particularly over the No. 30 and No. 60 [600- and 300-μm] sieves, where RCA fines tend to be deficient (*55*). The effects of mix design modifications on concrete strength are illustrated in Table A.5.4, which presents data from and FHWA-sponsored study of field test sites (*56*).

TABLE A.5.4
Effect of mixture design modifications on RCA concrete strength

	CT		KS		WY	
	RCA	**Nat**	**RCA**	**Nat**	**RCA**	**Nat**
w/(c+p)	0.40	0.45	0.41	0.41	0.38	0.44
%Fine RCA	0	0	25	0	22	0
f'c (MPa)	39.2	35.4	47.9	43.7	48.7	44.7

A.5.4. Considerations for Using Fine RCA in Concrete Mixtures

The use of fine RCA in concrete mixtures has generally been associated with mixture workability problems, reductions in concrete strength and elastic modulus, and significant increases in volumetric instability (i.e., shrinkage, creep and coefficient of thermal expansion). These behaviors can be attributed to the high mortar content that is generally present in RCA fines, as well as to the angularity, rough surface texture and high absorptivity of the particles.

The study by Etxeberria et al. (*10*) avoided using fine RCA (100% passing 3/8-in sieve) due to its high absorption that may have led to higher drying shrinkage. Smith and Tighe (*5*) observed that RFA contained many impurities and its use resulted in strength loss in the concrete. Zaharieva et al. (*41*) noted that the use of fine recycled aggregate is rarely allowed because it is the main cause of RAC problems, and avoiding the use of fine RCA can reduce the challenges of using RCA in concrete.

Most of the challenges related to RAC can be mitigated or completely offset through:

- mix design modifications (as described previously) especially reductions in water-cementitious material ratios and the use of chemical and mineral admixtures,
- structural design modifications (e.g., reductions in panel length and/or width to compensate for increased curl/warp stresses, increased reinforcement quantities, increased thickness, improved support, etc.), and
- restrictions on fine RCA content (typically to 30 percent or less replacement of natural fine aggregate) (*2*).

The ability to offset these behaviors was demonstrated with the 100 percent replacement of natural aggregate by RCA (both coarse and fine) on a major US highway in 1995, when the Texas DOT (TxDOT) successfully replaced a distressed portion of Interstate 10 near Houston with continuously reinforced concrete pavement (CRCP) using all recycled aggregate in the concrete mixture. TxDOT required that the RCA meet the same specification requirements as natural aggregate intended for use in concrete pavement construction. The contractor initially had some difficulty in producing RCA concrete with consistent workability. These problems were found to be due to inadequate moisture control of the recycled aggregate stockpiles. The situation was remedied with the installation of improved stockpile sprinkler systems. No significant adjustments in paving operations were required by the use of 100 percent coarse and fine RCA in the concrete (*30*).

In 2007, after 12 years of service, the performance of the RCA CRCP was described as excellent, with tight crack widths, few minor spalls, no punch-outs and no meandering cracks or spalls. The relatively low elastic modulus of the RCA concrete and the good bond between the old and new mortar are considered key factors in the excellent performance of this pavement to date (*30*).

It should be noted that this project made TxDOT aware of the sensitivity of concrete strength and workability to fine RCA content. As a result, in 1999, TxDOT adopted a special provision to limit the fine RCA content in concrete mixtures to 20 percent of all fine aggregate. Nevertheless, this project demonstrated that RCA fines could be used successfully at high replacement rates for natural sand in concrete mixtures if proper steps were taken in the design and construction of the pavement structure.

Concrete crushing operations can produce 60 percent or more fine recycled aggregate. From an environmental standpoint, it is essential that RCA fines be utilized completely. From a sustainability standpoint, it makes sense to use them (to the extent possible) in the highest possible application (i.e., in new concrete mixtures at replacement rates of up to 30 percent for natural aggregate, rather than in fill and soil stabilization applications).

A.5.5. Use of RCA in Two-lift Concrete Pavement Construction

Two-lift concrete paving involves the placement of two layers of concrete (wet-on-wet) instead of placing a single homogeneous layer, as is typically done in the U.S. The bottom layer typically comprises 80-90 percent of the total pavement thickness and generally contains locally available or recycled aggregates that are typically available at a lower cost but may not be suitable for use in wearing surfaces. Since the bottom lift is usually subjected to less environmental exposure, a wide range of recycled aggregates (including both recycled concrete and asphalt) can be used without sacrificing the durability of the pavement system. The top layer is typically relatively thin and usually contains dense, wear-resistant aggregates that provide excellent durability, reduced noise and increased pavement surface friction. These aggregates are typically more expensive and are often imported, but their impact on the overall pavements system cost is usually low because they are required in relatively small quantities.

While a handful of two-lift concrete paving projects have been constructed in the U.S., only one is known to have incorporated recycled concrete aggregate in the pavement structure: U.S. 75 in Iowa, which was built in 1976. This project incorporated about 60 percent recycled concrete and 40 percent recycled asphalt pavement in the 9-inch lower lift and all virgin materials in the 4-in. top lift. The upper lift was paved 24 ft. wide and encapsulated the 23-ft. lower lift. This pavement is still in service today.

This application is much more common in Europe (especially Austria), where the practice began with reconstruction of the Salzberg-Vienna A-1 concrete motorway in the late 1980s reusing 100 percent of the old concrete (*57*). A two-lift concrete pavement system was developed that used the crushed pavement (both asphalt and concrete) particles sized 4 mm–32 mm in a 19-cm [7.5-in.] lower lift, which was capped with a 3-cm [1.2-in.] surface layer of high-quality concrete which was used to produce an exposed aggregate surface for friction and noise reduction. The crushed pavement fines (sized 0 mm–4 mm) were mixed into the old pavement frost blanket to stabilize it (*57*).

Savings of natural materials on the first project alone were estimated at 205,000 metric tons of gravel, and associated savings of 30,000 trucking operations. Overall savings were estimated at a minimum of 10 percent when compared to the conventional use of natural aggregate. The success of this project led to construction of 75 km of roadway in the Salzburg and Lower Austria provinces between 1991 and 1994 and two-lift paving using recycled materials in the lower lift is now standard practice in Austria.

A.6. SUMMARY

Below summarizes some of the main points from this review of pertinent publications regarding concrete made with recycled concrete aggregate are as follows:

1. Using RCA promotes sustainability by reducing waste that may otherwise ended up in the landfill, conserving natural aggregate, and reducing greenhouse gasses, energy consumption and production costs related to using natural aggregate.
2. RCA has different properties than NA due to attached mortar on the RCA. Specific gravity of RCA is generally less, and adversely, the absorption of RCA is generally higher than natural aggregate.
3. The fresh concrete properties that may change with the use of RCA include lower workability than NC due to its angularity, rough surface texture, and higher absorption capacity of RA. RAC may also have higher air content than NC due to the air in the old mortar attached on RA.
4. Hardened concrete properties of RAC may include lower strength (compressive, flexural, and tensile strength); higher shrinkage, creep, CTE and permeability; lower modulus elasticity and density. Generally RAC is less durable than NC.
5. Many studies have been conducted examining the properties of RAC using different RCA replacement levels up to 100 percent replacement. Some studies showed that limiting the RCA replacement to 20 or 30 percent may have less of an effect on the concrete properties when compared to concrete with 100% NA.
6. Some of the challenges in using higher percentages of RCA can be overcome by using fly ash as partial replacement of cementitious material, reducing the mortar content adhering to the recycled aggregate, adjusting the mix design and mixing process, and by not using the fine portion of RCA.
7. A study on several pavements constructed by five highway agencies (Connecticut, Kansas, Minnesota, Wisconsin and Wyoming) using RCA showed that the performance of these RAC pavements was comparable to the control pavement that contained only natural aggregate, even for pavements that contained RCA derived from D-cracked and ASR-damaged pavements.

BUZZI UNICEM USA

PO Box 482-Greencastle, IN 46135-(765) 653-9766

This is to certify that **Type I** meets ASTM C-150 Specifications for Portland Cement and CSA A3000.

Chemical Data		Physical Data	
ASTM C114		ASTM C185	
Silicon Dioxide (SiO_2)	18.94	Air Entrained (%)	9.8
Aluminum Oxide (Al_2O_3)	5.65	ASTM C204	
Ferric Oxide (Fe_2O_3)	3.29	Fineness (cm^2/gm)	3750
Calcium Oxide (CaO)	63.20	ASTM C151	
Magnesium Oxide (MgO)	3.13	Autoclave Expansion (%)	0.082
Sulfur Trioxide (SO_3)	3.43	Compressive Strength, PSI	
Loss on Ignition	1.13	ASTM C109 Mortar Cubes	
Sodium Oxide	0.34	1-Day	2790
Potassium Oxide	0.78	3-Day	4060
Insoluble Residue	0.35	7-Day	4690
Total Alkali as Na_2O	0.86	28-Day	
POTENTIAL COMPOUND COMPOSITI		ASTM C191	
		Setting Time:	
Tricalcium Silicate (C_3S)	61	Vicat	
Dicalcium Silicate (C_2S)	8	Initial, Min.	112
Tricalcium Aluminate (C_3A)	9	Final, Min.	225
Tricalcium Aluminoferrite(C_4AF)	10		

Silo	Bill of Lading	Tons	Date	Silo	Bill of Lading	Tons	Date
							11/19/2010

STATE OF INDIANA)
COUNTY OF PUTNAM)
Before me the undersigned, a Notary Public for Putnam County, State of Indiana personally appeared John J. Wachal and acknowledged the execution of the foregoing instrument this 18th day of November 2010.

Philip A. Clodfelter, Notary Public
My commission expires May 8, 2015.

To:

John J. Wachal

John J. Wachal
Quality Manager

Figure B.1 Mill certificate for the cement used.

Analytical Testing Service Laboratories, Inc.
P.O. Box 1118, Joplin, Missouri 64802
(417) 782-6573

Headwaters Resources, Inc
P.O. Box 3734
Alpharetta, GA 30023
1-770-475-8095

February 02, 2010

Attn: Carolyn Grant

Re: 9747- Schahfer 15 Fly Ash Sample 2000 Ton Composite - 12/1-31/09

	ASTM C-618 Class "C" Requirements	Actual
Fineness (+325 Mesh)	34% Max	11.00%
Moisture Content	3% Max	0.12%
Specific Gravity	****	2.62
Specific Gravity Variation	5% Max	0.73%
Loss on Ignition	6% Max	0.37%
Soundness	0.8% Max	0.01%
S.A.I., 7 Days	75% Min	97.20%
S.A.I., 28 Days	75% Min	101.80%
Water Req. % Control	105% Max	93.40%
Silica SiO_2	****	36.90%
Aluminum Oxide Al_2O_3	****	20.14%
Ferric Oxide Fe_2O_3	****	7.01%
Total	50% Min	64.05%
Sulfur Trioxide SO_3	5% Max	1.58%
Calcium Oxide CaO	****	24.60%
Magnesium Oxide MgO	****	5.47%
Available Alkalies as Na_2O	****	1.21%

We certify the above was tested in accordance with ASTM C-618 and AASHTO M295

Analytical Testing Service Laboratories, Inc.

John K. Cupp, Manager

Figure B.2 Mill certificate for the fly ash used in the project.

Essroc
Italicementi Group

Mill Test Report
Logansport
Type I Cement

3084 W. CR 225 South
Logansport, IN 46947
Tel (574) 753-5121
Fax (574) 722-2168

From: May 01 2012
To: May 31 2012

Description	Test Result		ASTMC 150 Specifications	ASTM Method
SiO2	20.3			C 114
Al2O3	4.9			C 114
Fe2O3	2.2			C 114
CaO	63.1			C 114
MgO	2.8		6.0 Maximum	C 114
SO3	2.8		3.5 Maximum*	C 114
C3S	58.5			C 150
C3A	**9.3**			C 150
Total Alkalis	0.18		0.60 Maximum	C 150
Autoclave Expansion (%)	0.26		0.80 Maximum	C 151
14-Day Mortar Bar Expansion	0.013		0.020 % Maximum	C 1038
Time of Set (Vicat)				C 191
Initial Set (Minutes)	112		45 Minimum	
Final Set (Minutes)	225		375 Maximum	
Compressive Strength	PSI	MPa		C 109
1 Day	1510	10.4		
3 Day	3160	21.8	1740 PSI / 12.0 MPa Minimum	
7 Day	4380	30.2	2760 PSI / 19.0 MPa Minimum	
28 Day	5890	40.6		
Air Content (%)	9.1		12 Maximum	C 185
Fineness, Blaine (m2/kg)	**407**		280 Minimum	C 204
Loss on Ignition	1.4		3.0 Maximum	C 114
Insoluble Residue			0.75 Maximum	C 114

* When C3A is less than 8%

This is to certify that Portland Cement Type I meets the requirements of ASTM C 150 Standard Specification for Portland Cement.

Physical Test By: Tom Wisler

Chemical Test By: Tom Wisler

Louis A Jany

Lou Jany
Sr. Quality Manager

Figure B.3 Mill test report for the cement used in the field trial placement.

TABLE B.1
INDOT approved concrete paving mixture designs supplied by contractors

Material	IMI	Berns Construction Co., Inc.
	Weight (lbs)/yd^3	
Cement	440	515
Fly ash	100	0
Water	226	226
Fine aggregate	1414	1494
Coarse aggregate	1700	1670
Air entraining agent, fl oz	0.125–4.0 (Micro-Air)	0.5–3.0 (Daravair 1400)
Water reducer, fl oz	1.0–3.0 (Glenium 3030)	2.0–6.0 (WRDA 20)

NOTE: These designs were used as a basis for development of laboratory (L) mixture proportions shown in Table B.2.

TABLE B.2
Mixture proportions for concrete made in the laboratory (lbs/yd^3)

Mixture designation	L-M1-1N1-C	L-M2-1R-C	L-M3-.3R.7N1-C	L-M4-.5R.5N2-F	L-M5-.3R.7N1-F	L-M6-.5R.5N2-C	L-M7-1R-F	L-M8-.3R.7N2-F	L-M9-1N2-F
Cement	515	515	515	440	440	515	440	440	440
Fly ash	—	—	—	100	100	—	100	100	100
Water	217	217	217	227	227	227	227	227	227
Fine aggregate	1500	1400	1440	1420	1420	1420	1370	1420	1420
Coarse aggregate #8 N1	1700	—	1190	—	1141	—	—	—	—
Coarse aggregate #8 N2	—	—	—	815		815		1141	1700
Coarse aggregate #8 RCA	—	1600	510	815	489	815	1570	490	—
Air entraining agent, fl oz	0.9	0.5	0.8	0.5	0.5	1.0	1.5	0.6	0.7
Water reducer, fl oz	2.5	2.5	5.5	1.5	1.5	3.0	3	1.5	1.5
w/cm	0.42	0.42	0.42	0.42	0.42	0.44	0.42	0.42	0.42
Slump, in	3	3.2	2.4	3.3	2.3	2.75	3.2	3.8	2.9
Air content, pressure method—ACF	6.5	6.5	7	6.1	6.7	6.7	6.7	7.5	6.5
Air content, volumetric method	6.75	6.25	—	6.25	6.5	6.75	6.7	6.25	7
Fresh concrete density (lbs/ft^3)	143.8	139.2	143.6	141.6	142.3	140.4	135.3	140.7	143.4
7-day flexural strength, psi	—	—	698.8	643.5	693.5	725.5	617.5	614.7	675.5

ACF = aggregate correction factor.
— = missing data.
NOTE: Air entraining agent and water reducer: fl oz/100 lbs cementitious.

APPENDIX C. AGGREGATE TEST RESULTS

Figure C.1 (a) and (b) show respectively, the gradation curves for fine and coarse aggregate used in the study along with the associated INDOT specification limits for #23 and #8 aggregates. The #8 RCA used had less of the minus 4.75 mm size material than natural #8 aggregates used. The combined aggregate gradations for all mixtures used in this research fell within INDOT's upper and lower limit but when plotted against the "8-18" band [18], all gradations had excessive amounts of aggregate retained on ½ in. sieve and were deficient in material retained on the #8 (see Figure C.2).

Based on the coarseness factor (CF) and workability factor (WF) chart all combined gradations used, were classified as sandy gradation (see Figure C.3). Their CF ranged from 71.5 to 74.8 and WF from 44.7 to 47.9. The proportions of the coarse to fine aggregates plays a big role in determining the characteristic of the combined gradation. In this research, the coarse to fine aggregates ratio was 53:47 by mass. The relatively high percentage (47%) of fine aggregate in mixtures tends to increase the workability factor since more fines means more aggregates passing #8 sieve.

The L.A. abrasion test results given in Table C.1 indicate that #8N1 coarse aggregate was the most resistant to abrasion while #8R had the lowest resistance. Of the four aggregate sources used, it appears that aggregates with higher specific gravity were more resistant to L.A. Abrasion degradation (shown in Figure.C.4). All the aggregates satisfied INDOT's L.A. abrasion test requirement for AP aggregate which limits the mass loss to 40% (*16*).

INDOT's maximum allowable mass loss for ITM 209, Soundness of Aggregates by Brine Freeze and Thaw for #8 AP aggregate is 30% and for fine aggregate is 12%. The data presented in Table C.2 for #8N1 is based on INDOT historical data from 2001 to 2009, while for #23 sand is based on INDOT historical data from 2004 to 2010 for aggregate taken from the same source and produced by the same producer. The test results presented for 8N2 and 8R are based on tests completed on material used in this study. All aggregates used in this study passed INDOT's requirements for AP aggregate and use in concrete paving.

INDOT specifications for AP aggregate also requires passing the sodium sulfate soundness test with 12% loss or less, but by option of the Engineer the brine freeze and thaw test may be accepted. Other researchers have found that sulfate soundness tests do not accurately determine RCA quality (*2*) therefore only the brine freeze and thaw test were considered in this study.

As seen in the results for the organic impurities test shown in Figure C.5, the colors of the liquid of three samples are lighter than No. 3 standard organic plate color. These results indicate that the sand used in this research does not contain high level of organic compound which might possibly harm the concrete.

The well-developed modal analysis method of point counting was used (*17*) to determine what percentage of the RCA used for this study was old mortar, what percentage was original aggregate and what percentage was aged asphalt or other material.

The average D_{50} aggregate size of the RCA used in this project was approximately ½-in. (i.e., the ratio of percent passing to percent retained on the ½-in. sieve was approximately 50:50). First the RCA was split into two different size fractions, plus ½-in. and minus ½-in., from which 6-in. diameter cylinders were made using epoxy as the binder. Each cylinder was sliced into 1-in. thick sections and the sawn surfaces ground smooth to create a flat surface for examination (as shown in Figure C.6). A grid pattern was established over the sawn surface and an observation made at each point that the grid lines intersected. Slight magnification was used when necessary for proper identification (results are summarized in Table C.3).

The combined total values shown in Table C.3 are based on the assumption that 50% of the aggregate passed and 50% was retained on the ½-in. sieve. Nearly 30% of the RCA is old mortar and 2.6% is aged asphalt. There was a slightly higher percentage of old paste in the smaller sized RCA, and the majority of the asphalt pieces were in the smaller sized fractions.

To determine the water soluble ions concentration of coarse aggregates used in this research, the coarse aggregates were crushed and 20 grams of crushed aggregate passing #100 sieve from each aggregate was diluted with 40 ml of deionized water. The material was soaked overnight and was centrifuged to separate the liquid and the solid particles. Finally, the liquid was filtered and the final solution sampled for testing. The potassium ion was determined by using Atomic Absorption/Emission Spectrophotometer (Varian® SpectrAA–20) while the chloride and sulfate ions were measured by using Dionex Ion Chromatograph with Ionpac® AS4A Analytical column.

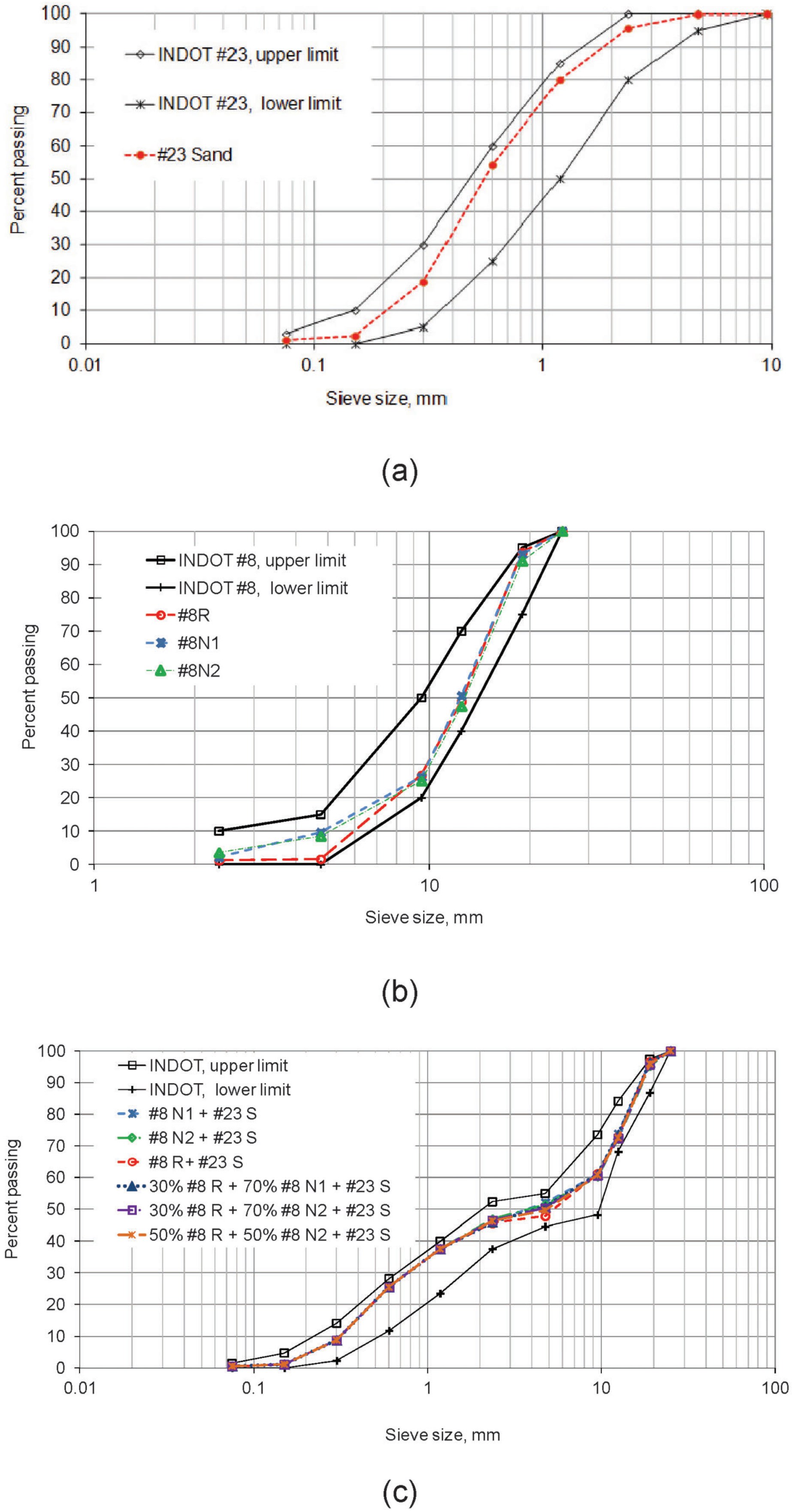


Figure C.1 Aggregates gradation curves for (a) fine aggregate; (b) coarse aggregate; (c) combined aggregate gradations (laboratory and plant mixtures).

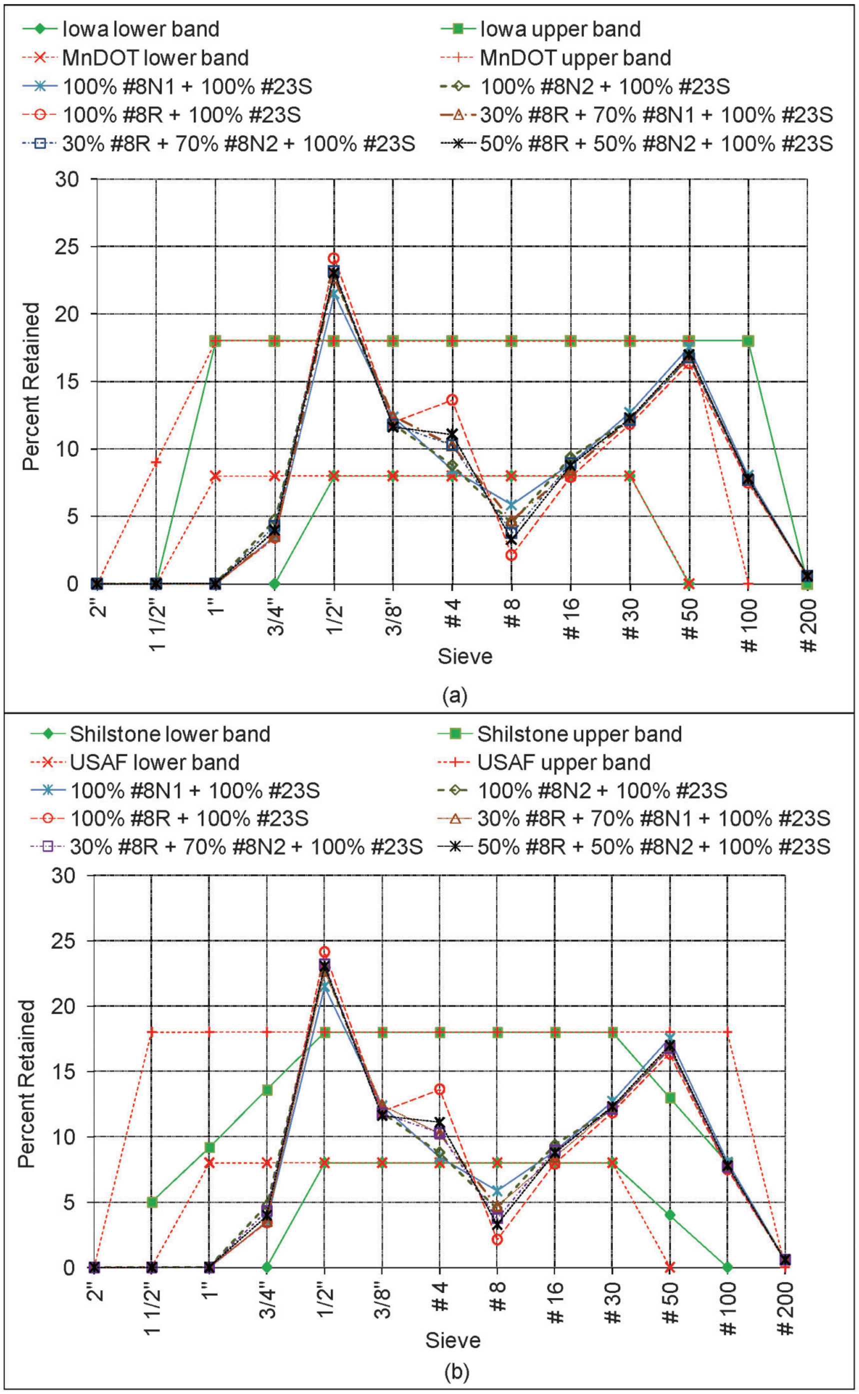


Figure C.2 Combined aggregate gradations of plant mixtures subjected to "8-18" bands; (a) Iowa and MnDOT "8-18" bands, (b) Shilstone and USAF "8-18" bands.

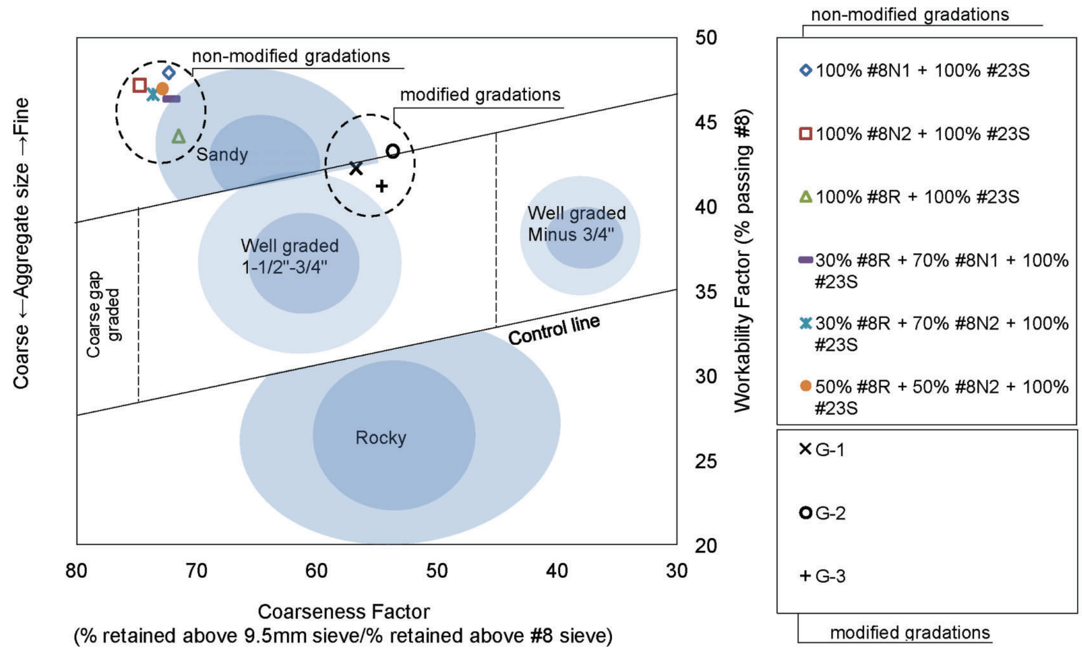


Figure C.3 Coarseness and workability factors for modified (G-1, G-2 and G-3) and non-modified gradations.

TABLE C.1
L.A. abrasion test results

Abrasion test (AASHTO T 96)					
Coarse aggregate	**Sample**	**Original mass, OD (gr)**	**Final mass, OD (gr)**	**Mass loss, %**	**Average mass loss, %**
#8 N1	1	5001	3571	29	29
	2	5000	3559	29	
#8 N2	1	5001	3471	31	31
	2	5000	3457	31	
#8 R	1	5000	3177	36	36
	2	5001	3182	36	
#11 R	1	5002	3298	34	34
	2	5002	3294	34	

TABLE C.2
Soundness of aggregates by brine freeze and thaw

	% mass loss	
Aggregate	**Actual value**	**INDOT max. limit**
#8N1	0.1–0.5*	30
#8N2	0.9	30
#8R	16.4	30
#23 Sand	0.9–9.5*	12

*From INDOT historical data.

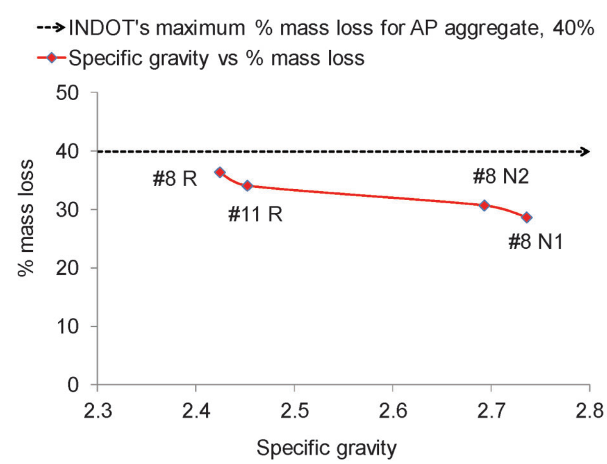


Figure C.4 Specific gravity of coarse aggregates vs. % mass loss during L.A. abrasion test.

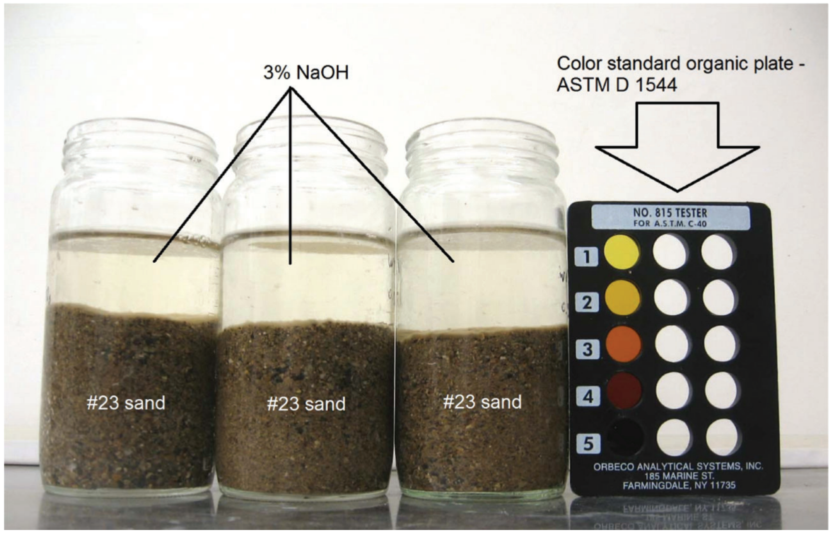


Figure C.5 The comparison between the color of deleterious samples with standard color organic plate.

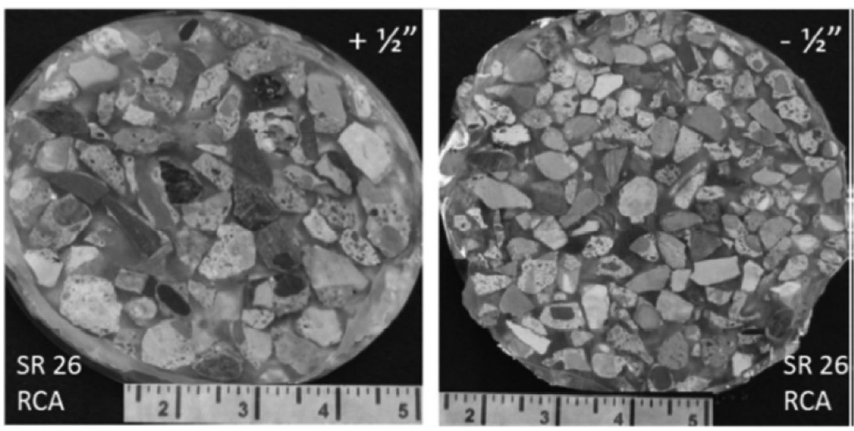


Figure C.6 Examples of the sawn and ground surfaces of #8 RCA embedded in epoxy examined for determining the percent mortar.

TABLE C.3
Point count results for estimating percent mortar attached to the RCA

RCA size fraction	# of particles examined	Mortar-free aggregate surface	Mortar present on aggregate surface	Aged asphalt	% of total mass
+1/2-in	176	71.6%	27.4%	1.0%	51%
- 1/2-in	183	65.2%	30.5%	4.3%	49%
Combined total	359	68.5%	28.9%	2.6%	

APPENDIX D. CONCRETE TEST RESULTS

The average unit weight of fresh concrete decreased as the amount of RCA increased as shown in Figure D.1.

The percent air for the fresh concrete was measured using both the volumetric and the pressure meter method. The difference in results between these two methods was small, and varied from 0.0% to 0.75% air with an average difference of 0.27% air for 18 different concrete mixtures (see Figure D.2). No trend is apparent.

The air dry density of plain concrete decreased by approximately 5.4% when N1 coarse aggregate was replaced by 100% RCA (from 148.9 lbs/ft^3 vs. 140.9 lbs/ft^3) (as shown in Figure D.3). The density of fly ash concrete decreased by approximately 3.5% when N2 coarse aggregate was replaced by 100% RCA (145.5 lbs/ft^3 vs. 140.4 lbs/ft^3 respectively).

Rapid Chloride Permeability (RCP) test results—all charges passed presented in this document have been adjusted for the "joule effect" which accounts for change in the conductivity of the solution with the change of the temperature during the test (*58*). The final passing charges were derived from Eq. D.1 (*58*).

$$\boldsymbol{Q}_0 = e^{\left[\ln(Q_{c6hr}) + \beta\left(1/\delta T - 1/273\right)\right]} \tag{D.1}$$

Where:

Q_0 = joule effect adjusted charge passed during the 6-hour RCP test

β = experimental constant equal to 1,245

Q_{c6hr} = original charge passed through the 6-hour RCP test

δT = difference in temperature increment (in Kelvin) during the 6-hour test

Although the coulomb value changed when Joule affect was taken into account this change did not alter chloride ion penetrability rating in any of the samples tested (as shown in Table D.2).

The results of the RCP test can also be used to calculate the equivalent steady-state chloride diffusion coefficient from Nernst-Plank equation (Eq. D.2) (*58*). The chloride diffusion coefficient is an important parameter that can be used to predict the time of corrosion initiation.

$$D = \frac{RTKV}{zC_0F(E/L)A} \tag{D.2}$$

Where:

R: universal gas constant (8.314 joule/mole/K [1.98 calorie/K/mole])

T: the absolute temperature in Kelvin

V: volume of the solution (250 ml)

z: valence of chloride ions (in this case z = 1)

C_0: chloride ion concentration (0.51 mole/l [14.52 mole/ft^3]),

E: applied electrical potential (60 Vdc)

F: Faraday constant (96485.3415 sA/mole)

L: thickness of the concrete specimen (2 in. [50 mm])

A: area of the sample exposed to NaCl solution

K: chloride migration rate (mol/L/s)

The chloride migration rate itself can be determined by using formula in Eq. D.3 (*58*).

$$\boldsymbol{K} = \frac{JA}{V} \tag{D.3}$$

Where:

J: flux of the chloride ion

A: area of the sample exposed to NaCl solution

V: volume of the solution (250 ml)

The ionic flux of chloride ion (J) can be calculated by Eq. D.4 (*58*).

$$J = \frac{I}{zFA} \tag{D.4}$$

Where:

I: adjusted average electrical current, $I = \dfrac{Q_0}{time\ of\ \exp eriment(s)}$ (*58*)

A: area of the sample exposed to NaCl solution

V: volume of the solution (250 ml)

The calculated values of the chloride diffusion coefficient for each of the plant mixtures used in the study are given in Table D.3.

The diffusion coefficient indicates the rate of the ion to penetrate through the concrete matrix. The higher the diffusion coefficient the faster it can penetrate the concrete.

An attempt to find a quicker and simpler way in determining the RCP test results was done in this study by predicting the final charge passed. The final passing charge was predicted by using the simple formula as shown in Eq. D.5 (*58*).

$$Q_{pred} = I_0 \times t \tag{D.5}$$

Where:

Q_{pred} = predicted passing charge, Coulomb

I_o = initial current (measured at the start of the experiment mA)

t = time of experiment, seconds (6 hrs = 21600 s)

Another approach to predict the total charge passed in an easier way was by finding the correlation between charges passed with theoretical bulk resistance (R). The bulk resistance of the concrete can be calculated simply by using formula in Eq. D.6 (*59*).

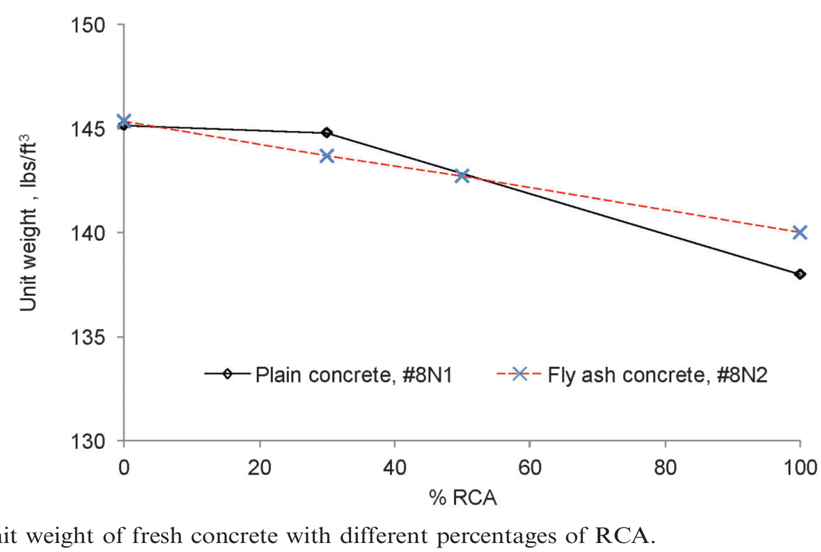


Figure D.1 Average unit weight of fresh concrete with different percentages of RCA.

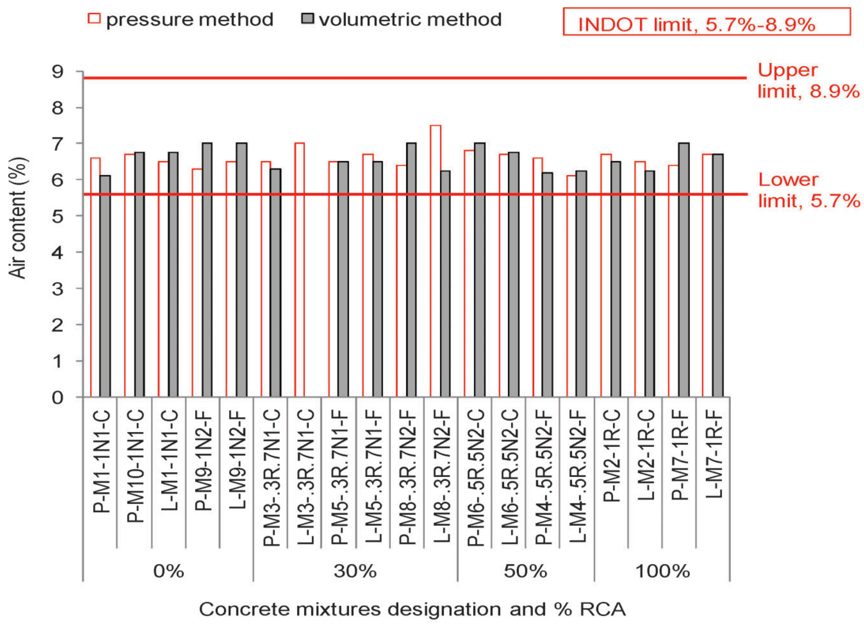


Figure D.2 Comparison between volume and pressure method results of % air in fresh concrete.

$$R = \frac{V}{I} \quad \text{(D.6)}$$

Where:
R: bulk resistance, ohm
V: applied voltage, 60 Volt
I: initial current, ampere

As expected, the relationship between bulk resistance and charge passed from RCP test results is linear (see Figure 2.5). This is because both of these tests are measuring the same property, i.e., the conductivity of the pore solution. The higher values of the bulk resistance are associated with lower cumulative charge passed.

Rapid chloride migration (RCM) test was conducted to confirm the reliability of RCP test results due to the consideration of Joule effect that might occur during RCP test which may lead to inaccurate test results as discussed in previous section.

The results of RCM test were obtained using 56-day-old samples. Instead of using a special test cells as specified in NT build 492 (*23*), the tests were performed with the same set of cells used for the RCP test (see Figure D.6). Except for this modification, the remaining parts of the test itself complied with the requirements of the NT build 492.

Parameters obtained from the experiment are charge passed, temperatures and currents applied during the experiment. After the test finished (generally after 24 hours), the specimen was split axially into two pieces in order to measure the penetration depth of chloride ions. The freshly split section of the sample was then sprayed with silver nitrate. The average depth of chloride ion penetration was measured from the mark made visible by the white silver chloride precipitate that became apparent after about 15 minutes of spraying. The average depth of chloride ion penetration along with the other obtained parameters then were used to determine the non-steady-state migration coefficient (D_{nssm}) using the formula in Eq. D.7 (*23*).

$$D_{nssm} = \frac{0.0239(273+T)l}{(U-Z)t}\left(\chi_d - 0.0238\sqrt{\frac{(273+T)l\chi_d}{U-Z}}\right) \quad \text{(D.7)}$$

Where:
D_{nssm}: non-steady-state migration coefficient, $\times 10^{-12}$ m^2/s
U: absolute value of the applied voltage, V
T: average value of the initial and final temperatures in the anolyte solution, °C

TABLE D.1
Chloride ion penetrability of concretes from different mixtures

Mixture designation	28 days		56 days	
	Final charge, Q (Coulomb)	Chloride ion penetrability	Final charge, Q (Coulomb)	Chloride ion penetrability
P-M1-1N1-C	4285	High	3208	Moderate
P-M2-1R-C	4826	High	4198	High
P-M3-.3R.7N1-C	3909	Moderate	2999	Moderate
P-M4-.5R.5N2-F	—	—	2255	Moderate
P-M5-.3R.7N1-F	2863	Moderate	2667	Moderate
P-M6-.5R.5N2-C	—	—	4469	High
P-M7-1R-F	4852	High	3152	Moderate
P-M8-.3R.7N2-F	3497	Moderate	2609	Moderate
P-M9-1N2-F	3213	Moderate	1799	Low
P-M10-1N1-C	3538	Moderate	3250	Moderate

NOTE: — = missing data.

TABLE D.2
RCP test 56-day results with and without temperature correction

Mixture designation	Final charge, Q (Coulomb)		Chloride ion penetrability
P-M1-1N1-C	3743	***3208***	Moderate
P-M2-1R-C	5785	***4198***	High
P-M3-.3R.7N1-C	3768	***2999***	Moderate
P-M4-.5R.5N2-F	2885	***2255***	Moderate
P-M5-.3R.7N1-F	2925	***2667***	Moderate
P-M6-.5R.5N2-C	5009	***4469***	High
P-M7-1R-F	3665	***3152***	Moderate
P-M8-.3R.7N2-F	2910	***2609***	Moderate
P-M9-1N2-F	1893	***1799***	Low
P-M10-1N1-C	3643	***3250***	Moderate

NOTE: ***Boldface italics*** indicate with temperature correction. All samples were tested at 56-day.

L: thickness of the specimen, mm
x_d: average value of the penetration depth, mm
t: test duration, hour

The value of D_{nssm} indicates concrete resistance to chloride ingress. The D_{nssm} value can be used to classify concrete's resistance to chloride ion penetration into the following categories (*60*):

- $D_{nssm} < 2x10^{-12}$ m^2/s: very good resistance against chloride ingress
- $2x10^{-12}$ m^2/s $< D_{nssm} < 8.10^{-12}$ m^2/s: good resistance against chloride ingress
- $8x10^{-12}$m^2/s $< D_{nssm} < 16.10^{-12}$ m^2/s: moderate resistance against chloride ingress
- $D_{nssm} > 16x10^{-12}$ m^2/s: not suitable for aggressive environment (high)

Table D.4 lists the calculated values of the D_{nssm} for all plant mixtures used in the study.

Only one mixture (M6—plain concrete with 50% RCA) would be classified as not suitable for aggressive environment ($D_{nssm} = 16.9 \times 10^{-12}$ m^2/s). This value is about 36% higher than the control concrete (M1 - $D_{nssm} = 12.4 \times 10^{-12}$ m^2/s). All others concretes can be classified as having moderate resistance against chloride ion penetration.

The fly ash concretes had lower D_{nssm} than plain concrete with the same amount of RCA (M9 vs. M1 and M10, M5 and M8 vs. M3, M4 vs. M6), except for concrete with 100% RCA (M7 vs. M2). For concrete with 50% RCA, the D_{nssm} of plain concrete (M6) was 44% higher than the fly ash concrete (M4). This trend indicated that fly ash improved the chloride ion penetrability resistance of RCA concrete when the portion of RCA is up to 50% of the total coarse aggregate.

For plain concrete, the high variability in the results made it difficult to predict the effect of RCA replacement levels on the chloride ion penetrability. In fly ash concrete, the presence of 30% RCA (M5 and M8) did not show significant effects on the D_{nssm} (up to 9% difference) compared with the fly ash concrete without RCA (M9). The same trend occurred on for fly ash concrete with 50% RCA compared to fly ash concrete without RCA where the difference of D_{nssm} was about 7% (M4 vs. M9). A more significant increase (45%) of D_{nssm} values was found when comparing the fly ash concrete with 100% RCA (M7) to the fly ash concrete without RCA (M9). This is an indication that high levels of RCA (100% replacement level) worsened the chloride ion penetrability resistance of concrete even with the presence of fly ash.

Figure D.8 indicates that the resistivity based on surface measurements was higher than the resistivity determined based on EIS measurements. In addition to age, the difference in results may be due, in part, to the different way the samples were conditioned. The EIS samples (bulk resistivity samples) were conditioned the same way as the RCP samples (as per AASHTO T 277 (*61*)). The samples for surface resistivity measurement were taken directly from the curing room (23±2C and 95% relative humidity) just before performing the test. Although their surface remained moist during the test, it is very likely that the vacuum saturation applied to the EIS samples increased their saturation level and thus increased the conductivity (decreased the resistivity).

The length change measurements from the AASHTO T 161 concrete freezing and thaw test are shown in Figure D.9. As noted in Section 2.2.2.2 the comparator was damaged during the testing of the first five mixtures (P-M1, P-M2, P-M3, P-M4, and P-M5) and those length change measurements are invalid (showing unrealistic values, for example ±1.2% expansion for a known high quality AP aggregate and no evidence of cracking in the beams).

TABLE D.3
Average chloride diffusion coefficient

	Diff. coefficient, $\times 10^{-12}$ m^2/s (Nernst-Plank)	
Mixture designation	28 days	56 days
P-M1-1N1-C	1.05E-11	7.98E-12
P-M2-1R-C	1.18E-11	1.07E-11
P-M3-.3R.7N1-C	9.53E-12	7.56E-12
P-M4-.5R.5N2-F	—	5.54E-12
P-M5-.3R.7N1-F	7.01E-12	6.52E-12
P-M6-.5R.5N2-C	—	1.09E-11
P-M7-1R-F	1.19E-11	7.71E-12
P-M8-.3R.7N2-F	8.50E-12	6.36E-12
P-M9-1N2-F	7.83E-12	4.40E-12
P-M10-1N1-C	8.63E-12	7.95E-12

NOTE: — = missing data.

TABLE D.4
The non-steady-state migration coefficients (D_{nssm}) of concrete from the different plant mixtures

Mixture designation	D_{nssm} ($\times 10^{-12}$ m^2/s)	Classification of resistance to chloride ion penetration
P-M1-1N1-C	12.4	Moderate
P-M2-1R-C	10.6	Moderate
P-M3-.3R.7N1-C	11.8	Moderate
P-M4-.5R.5N2-F	9.5	Moderate
P-M5-.3R.7N1-F	9.2	Moderate
P-M6-.5R.5N2-C	16.9	Poor
P-M7-1R-F	14.7	Moderate
P-M8-.3R.7N2-F	11.1	Moderate
P-M9-1N2-F	10.2	Moderate
P-M10-1N1-C	16.0	Moderate

TABLE D.5
Test results from RCPT, RCM and EIS test

	Average charge passed, Coulomb			Average bulk resistance, Ohms		Nernst-Plank diff. coefficient ($\times 10^{-12}$)	Non-steady-state migration coefficient, D_{nssm} ($\times 10^{-12}$ m^2/s)	Resistivity, Kohm-cm EIS test	
Mixture designation	RCPT	RCPT*	CTH	RCPT	CTH	RCPT	CTH	RCPT's sample	CTH's sample
P-M1-1N1-C	3743	3208	5034	398	—	2.00	12.38	6.36	—
P-M2-1R-C	5785	4198	4789	302	430	0.89	10.63	4.83	6.85
P-M3-.3R.7N1-C	3768	2999	4901	410	—	0.47	11.81	6.54	—
P-M4-.5R.5N2-F	2885	2255	3802	467	470	1.39	9.50	7.45	7.49
P-M5-.3R.7N1-F	2925	2667	3852	548	605	1.63	9.24	8.75	9.65
P-M6-.5R.5N2-C	5009	4469	4681	335	321	2.73	16.89	5.34	5.12
P-M7-1R-F	3665	3152	6037	440	424	1.93	14.72	7.02	6.77
P-M8-.3R.7N2-F	2910	2609	5174	548	509	1.59	11.14	8.75	8.12
P-M9-1N2-F	1893	1799	3891	681	615	1.10	10.18	10.87	9.81
P-M10-1N1-C	3643	3250	5710	439	495	1.99	15.97	7.01	7.89

*With temperature correction.
NOTE: All samples tested at 56-day.

TABLE D.6
Average surface resistance and comparison between chloride ion penetrability of concretes based on surface resistivity test and RCP test

	Surface resistivity test		
Mixture designation	Surface resistance, K-ohm. cm	Chloride ion penetrability, (age of sample, days) (AASHTO TP 95)	Chloride ion penetrability (at 56 days, RCP test) (AASHTO T 277)
P-M1-1N1-C	—	—	Moderate
P-M2-1R-C	11.5	High (176)	High
P-M3-.3R.7N1-C	15.4	Moderate (174)	Moderate
P-M4-.5R.5N2-F	25.2	Low (155)	Moderate
P-M5-.3R.7N1-F	24.6	Low (126)	Moderate
P-M6-.5R.5N2-C	11.0	High (105)	High
P-M7-1R-F	13.8	Moderate (69)	Moderate
P-M8-.3R.7N2-F	14.1	Moderate (56)	Moderate
P-M9-1N2-F	15.6	Moderate (56)	Low
P-M10-1N1-C	12.1	Moderate (56)	Moderate

NOTE: — = missing data. Air entraining agent and water reducer: fl oz/100 lbs cementitious.

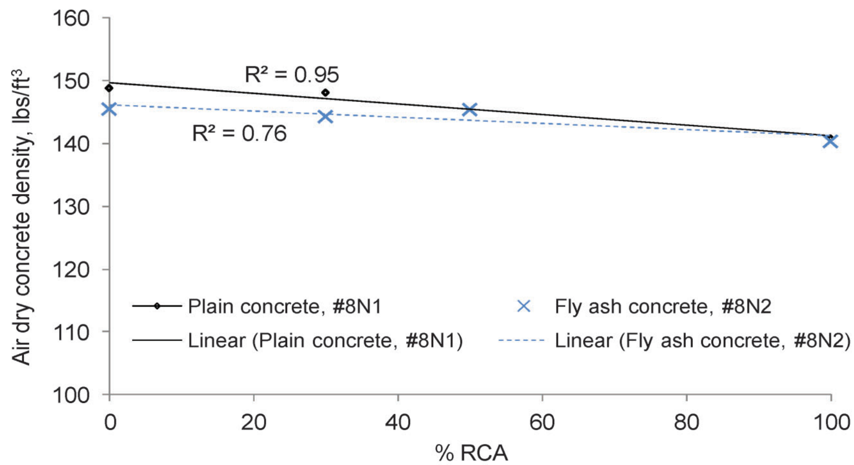


Figure D.3 Average air dry density of concrete with different percentages of RCA.

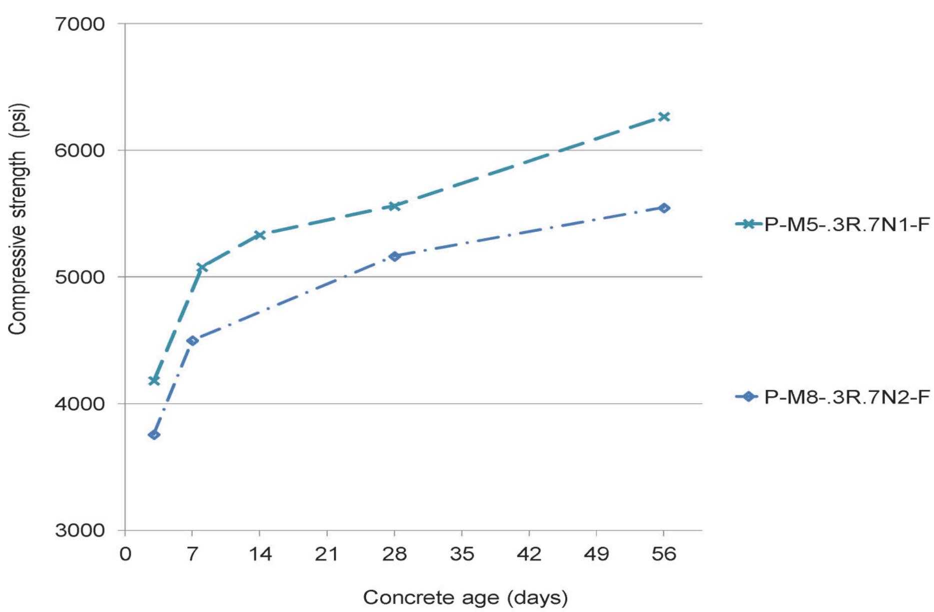


Figure D.4 Compressive strengths of concrete with different type of natural aggregates.

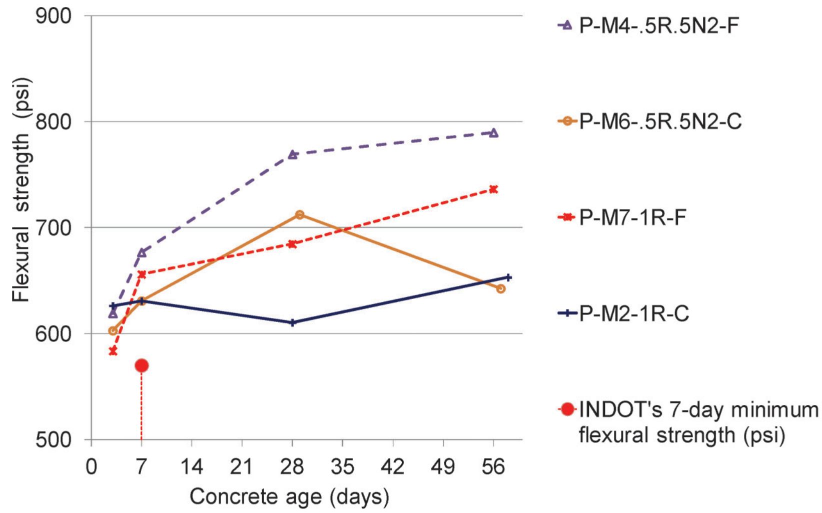


Figure D.5 Flexural strength of plain and fly ash concrete with 50% and 100% RCA content.

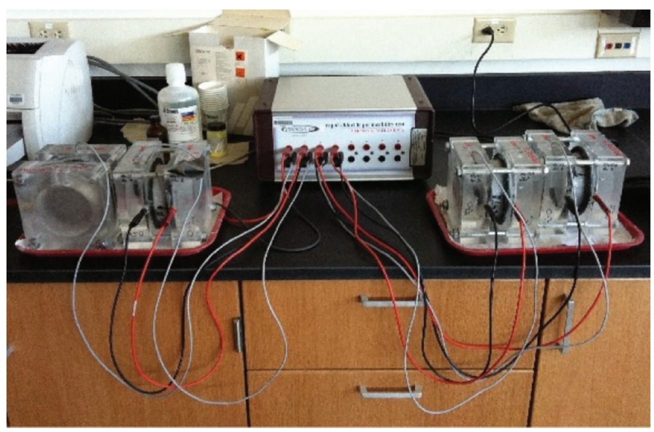


Figure D.6 RCM test setup.

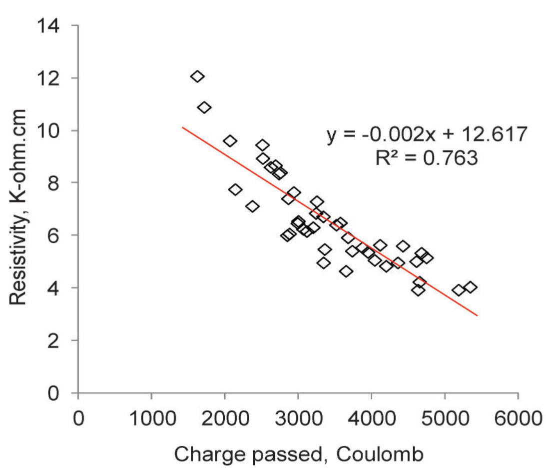


Figure D.7 Correlation between concrete's resistivity (from EIS test) and total charge passed (from RCP test).

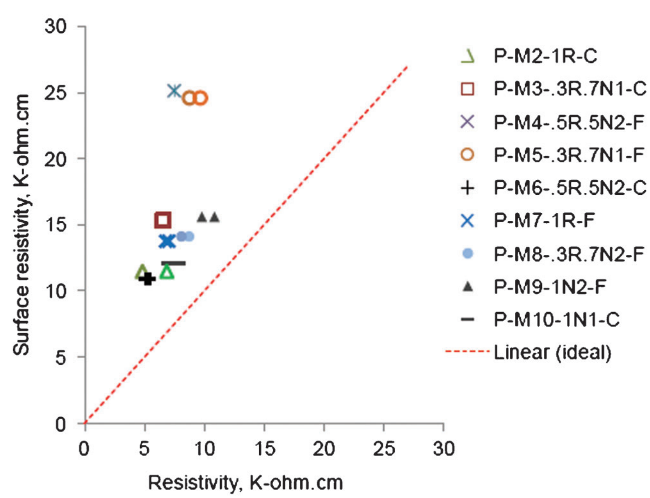


Figure D.8 Resistivity (56-day, EIS test) vs. surface resistivity.

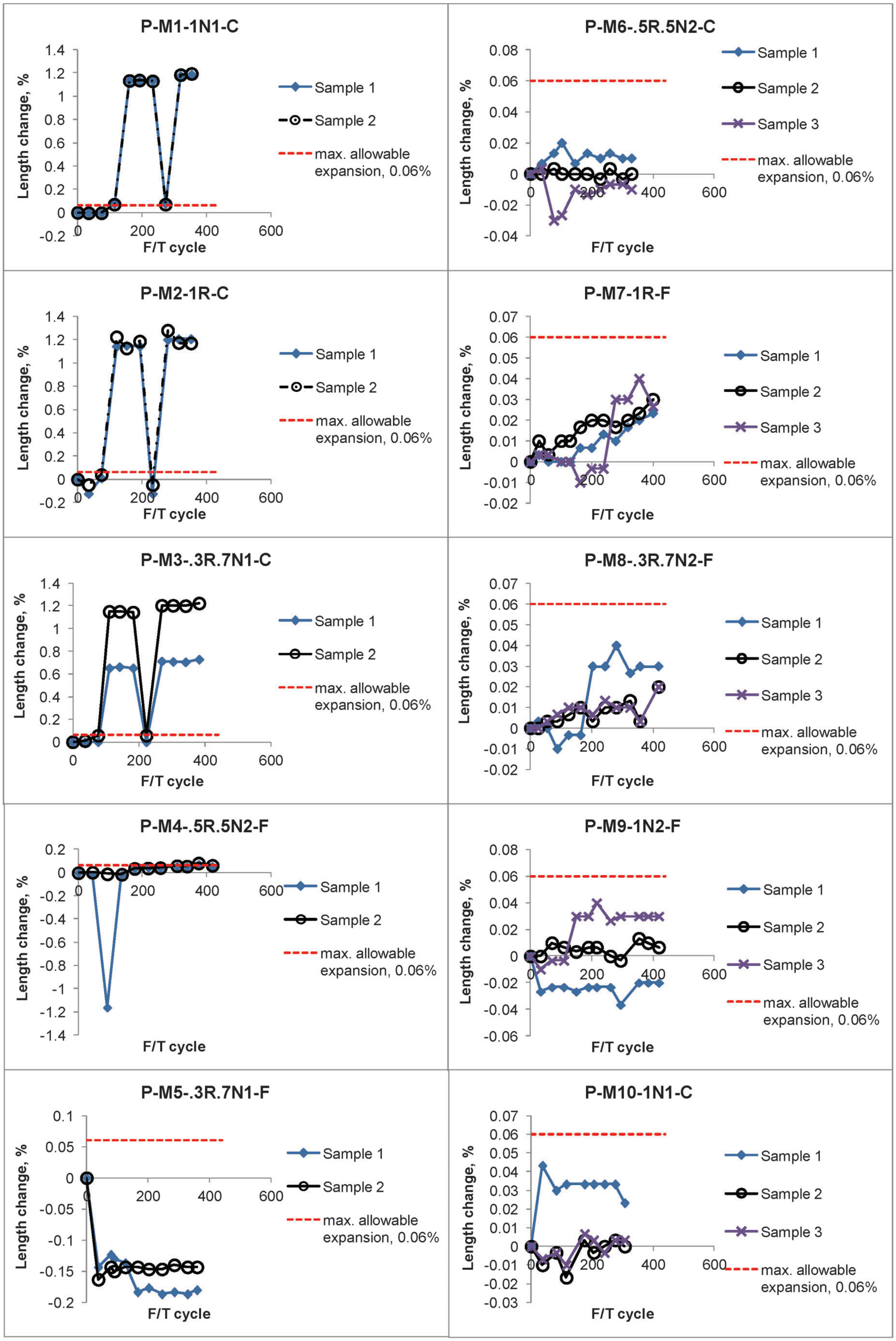


Figure D.9 Length change on F/T beams.

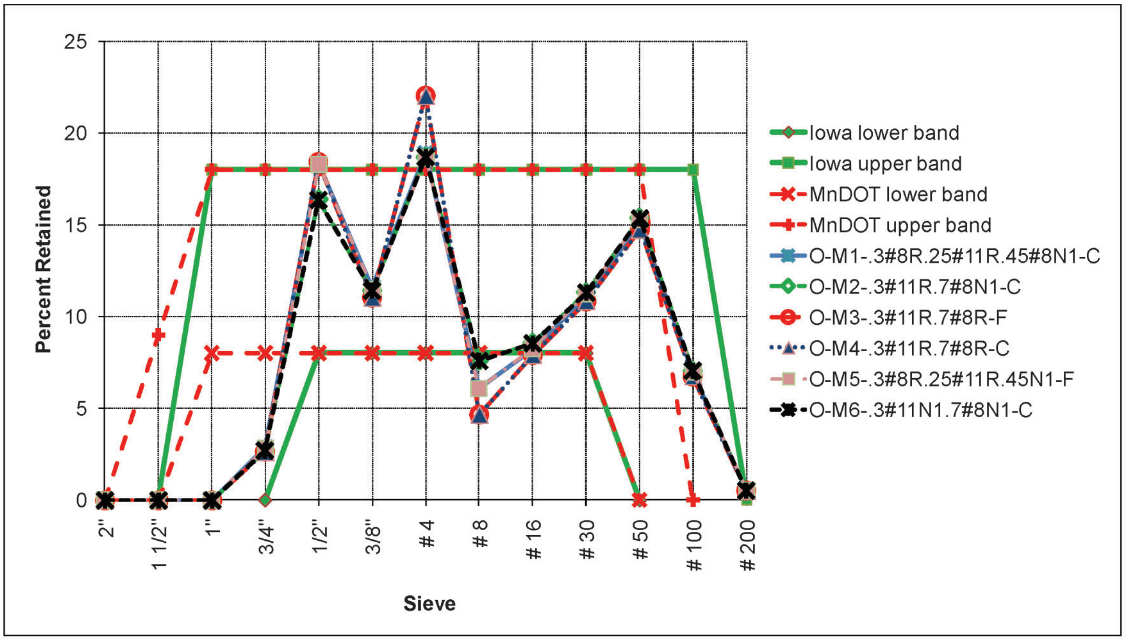
APPENDIX E. MODIFIED GRADATION

The replacement levels of RCA used in the mixtures with modified gradations were 30% (OM-2), 55% (OM-1 and OM-5) and 100% (OM-3 and OM-4). The decision to use 55% (30%#8 + 25%#11) level of replacement in OM-1 and OM-5 (rather than 50%, which was used in the lab and plant mixtures), was based on the fact that this replacement level had been found to generate a gradation which was closer to well graded area on coarseness factor chart.

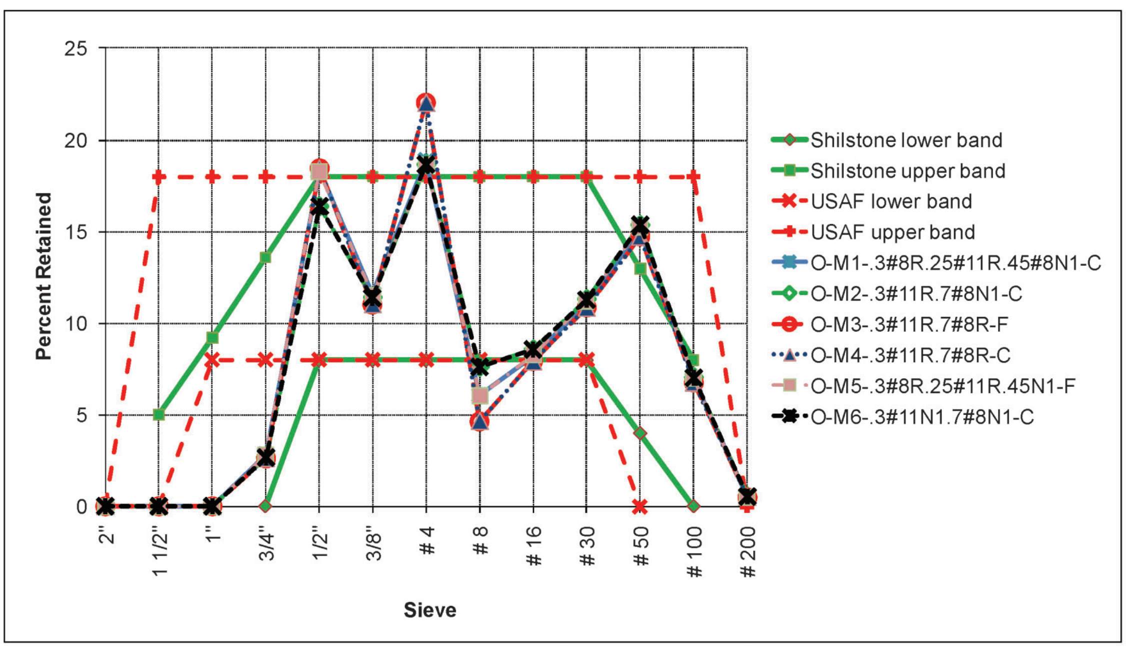
When compared to the lab and plant mixtures, the mixtures with modified gradation had 25%–30% (base on weight) of #11 aggregates as part of the coarse aggregates.

The modified gradations were more of continuous gradations and plotted closer to within the "8-18" band (as seen in Figure E.1).

The results of air content and slump of mixtures with modified gradations (from now on referred to as modified mixtures) are shown Table E.2.



(a)



(b)

Figure E.1 Combined aggregate gradations of optimized mixtures subjected to "8-18" bands; (a) Iowa and MnDOT "8-18" bands, (b) Shilstone and USAF "8-18" bands.

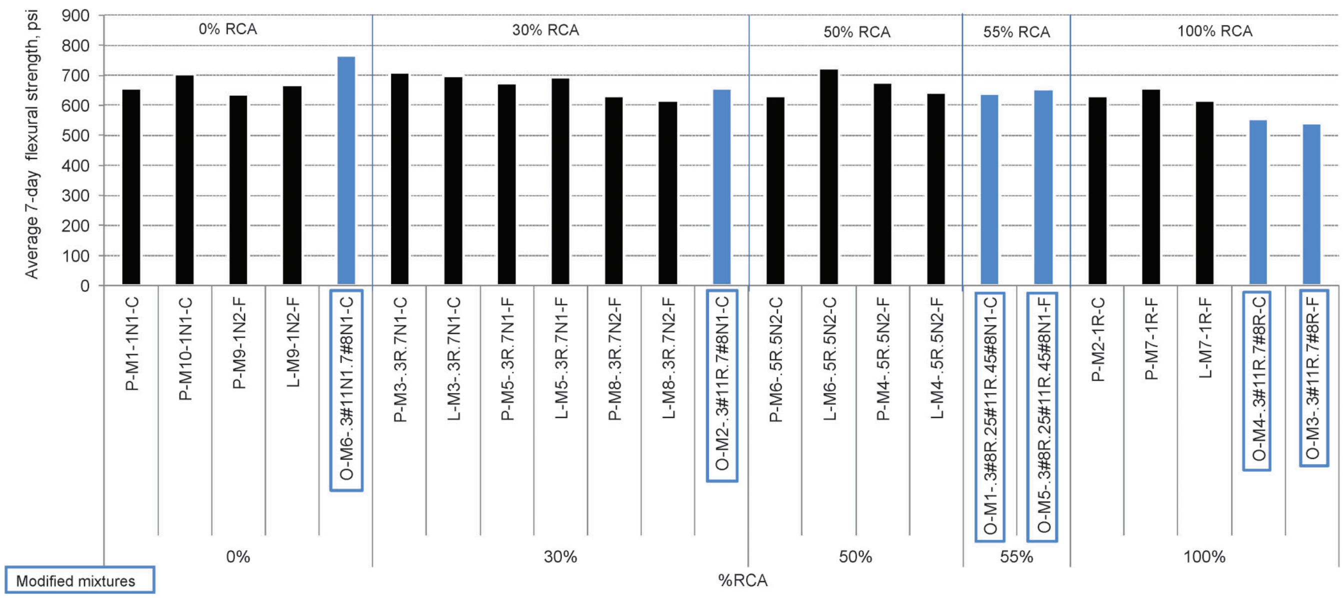


Figure E.2 The average values of 7-day flexural strength for concretes with non-modified and modified gradation.

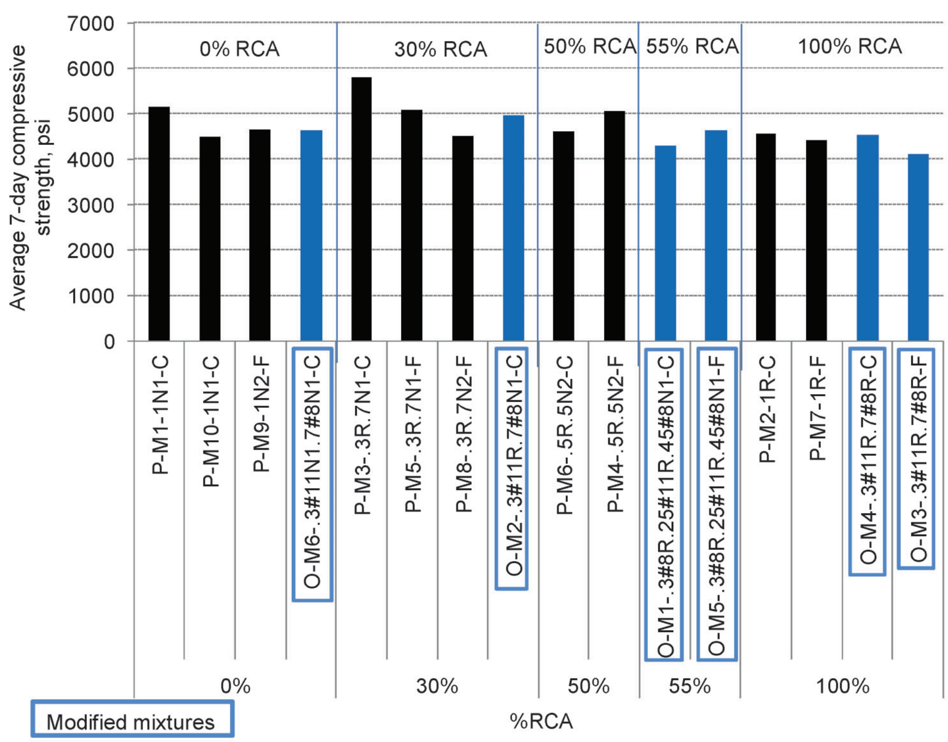


Figure E.3 7-day compressive strength of concretes from various mixtures.

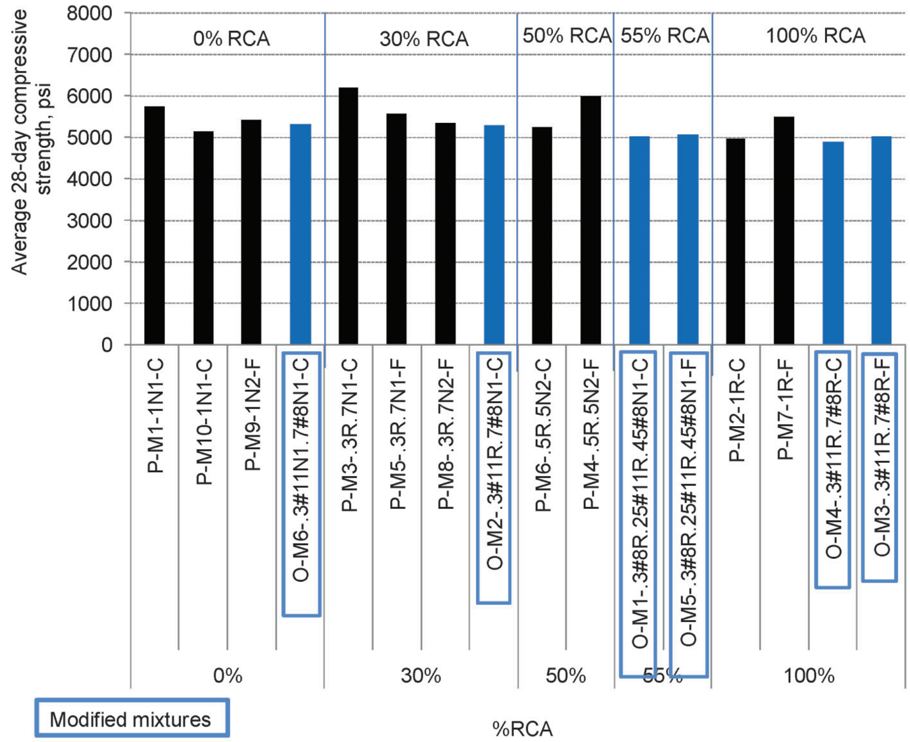


Figure E.4 28-day compressive strength of concretes from various mixture.

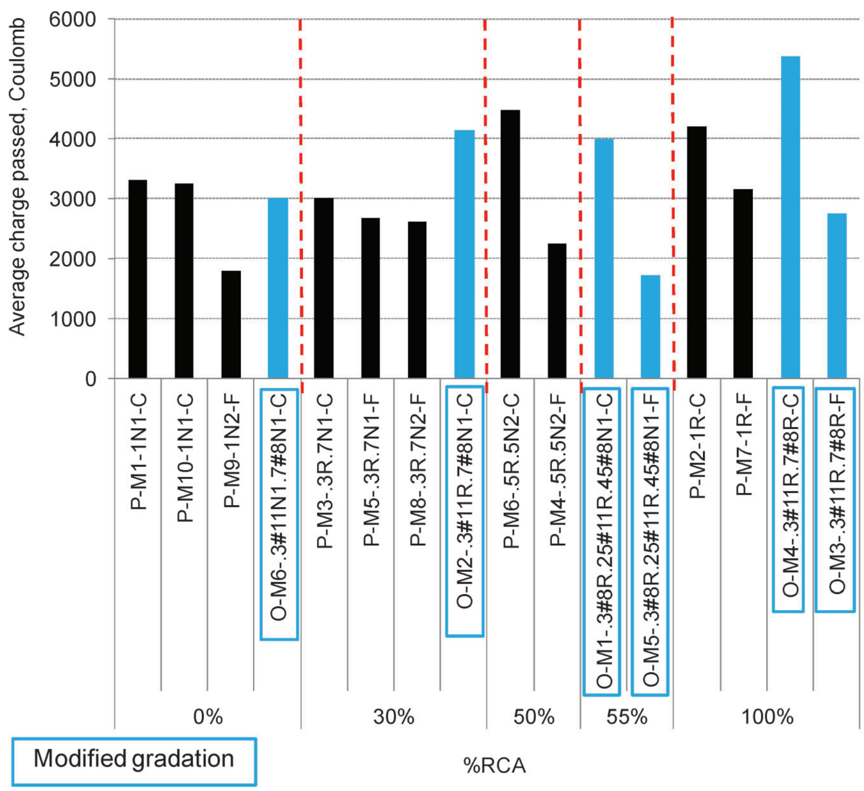


Figure E.5 The average values of charge passed for 56-day old concrete specimens from non-modified (plant) and modified gradation mixtures.

TABLE E.1
Mixture proportions with modified gradation for concrete made in the laboratory (lbs/yd^3)

Materials	O-M1-.3#8R.25# 11R.45#8N1-C	O-M2-.3# 11R.7#8N1-C	O-M3- .3#11R.7#8R-F	O-M4-.3# 11R.7#8R-C	O-M5-.3#8R.25# 11R.45#8N1-F	O-M6-.3# 11N1.7#8N1-C
Cement	515	515	400	515	440	515
Fly ash	—	—	100	—	100	—
Water	211.2	215.0	210.0	232.0	225.0	230.0
Fine aggregate	1330	1350	1300	1300	1320	1350
Coarse aggregate #8N1	790	1260	—	—	775	1300
Coarse aggregate #11N1	—	—	—	—	—	550
Coarse aggregate #8R	530	—	1200	1200	515	—
Coarse aggregate #11R	450	535	510	510	435	—
Combined gradation #	G-1	G-2	G-3	G-3	G-1	G-2
Air entraining agent, fl oz	0.8	0.5	0.9	0.9	0.8	0.8
Water reducer, fl oz	2.0	1.5	1.5	1.1	2.0	2.0
w/cm	0.41	0.42	0.42	0.45	0.42	0.45

NOTE: — = missing data.

TABLE E.2
Slump and air content values of mixtures with modified gradations

Mixture designation	O-M1-.3#8R.25 #11R.45#8N1-C	O-M2-.3# 11R.7#8N1-C	O-M3-.3# 11R.7#8R-F	O-M4-.3# 11R.7#8R-C	O-M5-.3# 8R.25#11R.45 #8N1-F	O-M6-.3# 11N1.7#8N1-C	Target range
Slump, in	3.3	1.75	3	1.5	1.7	1.5	1.25-3.00
Air content, % (volumetric method)	6.5	6	6.5	6	7	6.25	6.5 (5.7-8.9)*

*Allowable range.

TABLE E.3
Comparison of plastic and hardened concrete properties of modified and plant concrete

		O-M1 vs.P-M5		O-M2 vs. P-M3		O-M3 vs P-M7		O-M4 vs P-M2		O-M5 vs P-M4		O-M6 vs P-M1/10	
	WR	**2**	**1.7**	**1.5**	**2**	**1.5**	**2.4**	**1.1**	**2.0**	**2.0**	**2.1**	**2.0**	**1.9/2.0**
Phase	**w/cm**	**0.41**	**0.43**	**0.42**	**0.43**	**0.42**	**0.40**	**0.45**	**0.47**	**0.42**	**0.40**	**0.45**	**0.44/0.42**
Plastic	**Slump**	3.3 in	1.5 in	1.75 in	1.7 in	3.0 in	1.7 in	1.5 in	2.1 in	1.7 in	1.7 in	1.5 in	2.1/2.0
	Benefit	*Possible*		*Yes*		*Possible*		*Yes*		*No*		*No*	
Hardened	**Flexural**	Sl Increase		Sl decrease		Lg decrease		Decrease		Sl decrease		Lg increase	
	Compr	Decrease		Decrease		Sl decrease		Similar		Sl decrease		Similar	
	RCP	Sl improved		Worse		Sl improved		Worse		Sl improved		Sl improved	
	Benefit	*Possible*		*No*		*No*		*No*		*No*		*Yes*	

NOTE: Lg = largely; Sl = slightly.

APPENDIX F. BENEFIT-COST ANALYSIS MODEL

Appendix F is available here: http://docs.lib.purdue.edu/cgi/viewcontent.cgi?filename=1&article=3040context=jtrptype=additional

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,500 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at: http://docs.lib.purdue.edu/jtrp

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The recommended citation for this publication is:

Verian, K. P., N. M. Whiting, J. Olek, J. Jain, and M. B. Snyder. *Using Recycled Concrete as Aggregate in Concrete Pavements to Reduce Materials Cost*. Publication FHWA/IN/JTRP-2013/18. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, 2013. doi: 10.5703/1288284315220.